Engineering Guidelines for Predicting Erosion and Sediment Yields from Mining activities In Subalpine Areas

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Submitted to:

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This report has been prepared under the direction of Dr. Robert S. Johnston, Intermountain Forest and Range Experiment Station, (Contract No. 12-11-204-134).

The techniques proposed in these guidelines are applicable to a wide range of resource development activities in the subalpine zone of concern to the Forest Service which vary from silviculture to mining. Accordingly, valuable input for this study was obtained from several of my colleagues in the Forest Service who are currently working in non-point source pollution and forest hydrology. These include: Dave Falletti, Dave Rosgen, Chuck Troendle, Kerry Knapp, and Toby Hanes of the Watershed Systems Development Unit, and Ron Tabler of the Rocky Mountain Forest and Range Experiment Station. Their review of these guidelines and contributions of expertise and data are gratefully acknowledged.

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by

C. F. Leaf, P.E.

PREFACE

These guidelines discuss pertinent issues as they apply to water-related impacts from mining in the Rocky Mountain/Inland Intermountain Region. The potential impacts on these abiotic systems are considered <u>only</u> for normal or average conditions and <u>not</u> for critical situations such as flooding, severe storms, etc. A generic analytical framework is developed on a broad scale, and therefore, may not be completely valid at a site-specific level. The logic and analytical framework proposed in these guidelines are currently being developed by hydrologists who are actively engaged in evaluating environmental impacts.[1/],[2/]

[1/] Proceedings of Skywater Conference IX, <u>Weather Modification and the Environment</u>, USDI Bureau of Reclamation, Division of Atmospheric Water Resources Management, [Vail, Colorado, Nov., 1976]. (In press)

[2/] See EPA - Forest Service Interagency Agreement EPA-IAG-D5-0660. <u>Guidelines for Broadlevel Evaluation and Control Selection for Non-Point Source Pollution Associated with Silvicultural Activities</u>.

These guidelines are not a detailed discussion of the theory, but rather a systematic compilation of equations and procedures, which, despite the limited scientific data available, in most situations, appear to be adequate for engineering applications.

In the author's opinion, these guidelines are a realistic appraisal of the engineering tools available for quantitatively evaluating the impacts of mining on - water and sediment yield from subalpine watersheds. However, successful application of the methods proposed herein requires experience and judgment. Chapters 1 through 6 present theory, whereas Chapter 7 discusses field application of these guidelines. Appendices I, II, and III contain more specific data and procedures required for the solution of non-point source pollution problems.

CHAPTER 1

OVERVIEW OF WATER-RELATED IMPACTS RESULTING FROM MINING ACTIVITIES

The issues considered in these guidelines are basically those which refer to the physical processes that take place in a subalpine ecosystem having to do with the disposition of energy and water. Changes in these processes as the result of mining activities can then be translated into associated impacts on biological systems as, for example, fish and wildlife. A number of issues having to do with the water-related impacts are identified. Within the limitations of time, given the broad scope of the problem, a number of pertinent factors or processes associated with these issues will be considered in varying degrees of detail. The areas of concern in these guidelines are the subalpine watersheds of the"Rocky Mountain/Inland Intermountain Region", shown as the cross-hatched area in Figure 1.

Goals

The goals of these guidelines are to (1) suggest techniques that compare baseline conditions to potential changes in the hydrologic system, (2) to define the important linkages that exist between the various system factors or processes, and (3) present procedures for quantifying impacts on each identified factor. From these goals, alternatives for ecologically sound environmental management can be identified.

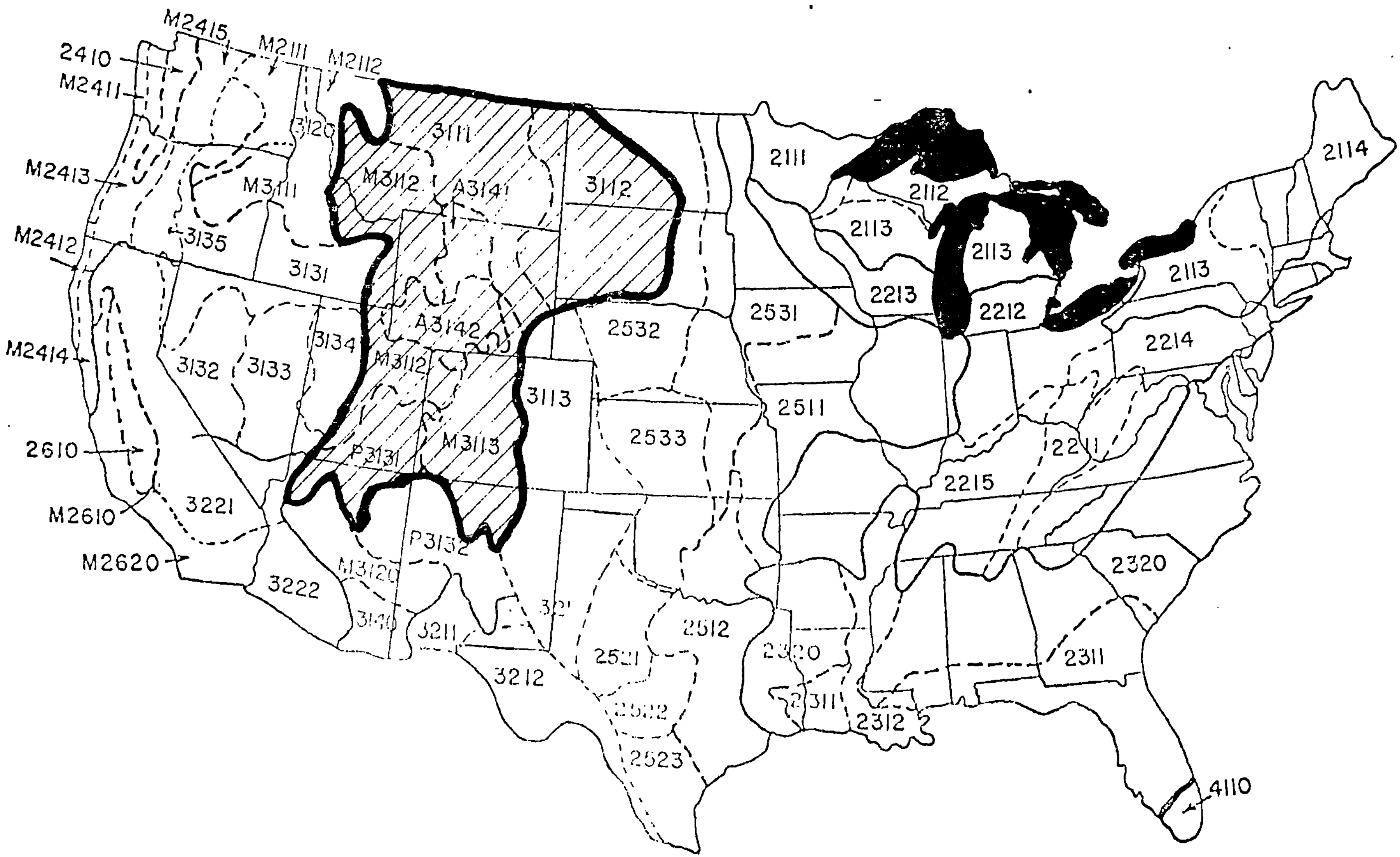


Figure 1.--Rocky Mountain/Inland Intermountain Subalpine Zone (subalpine environments within the cross-hatched area). Numbers refer to Bailey's vegetation classification (Bailey, 1976).

Assumptions

Certain assumptions were necessary to attain the goals listed above as follows:

A. If they are to be resolved, environmental issues related to the exploitation of natural resources must be treated in a process-oriented manner.

B. Discussions of these issues are limited strictly to those associated with water-related impacts.

C. The variables affected by mining activities are principally: vegetation, soil, and water.

D. These three basic parameters then become the inputs to an analytical framework from which baseline conditions and impacts can be predicted using available state-of-the-art technology.

E. It is assumed that the current status of knowledge will allow relative quantification adequate to determine most water-related environmental impacts.

F. Water-related environmental impacts attributed to mining activities can best be evaluated by considering departures from defined baseline or pretreatment conditions.

Methodology

The methodology proposed herein is to first identify those primary water-related issues that are pertinent to erosion and sediment yield subject to the assumptions stated above. Factors associated with these issues are then reviewed and summarized. A regionalized process-oriented approach is followed, since this allows one to perform a comparative analysis between different environmental settings and between "pretreatment or baseline conditions" and those created as a result of mining activities.

Issues

One of the first tasks of any impact analysis is the summarization of issues pertinent to water-related impacts on erosion and sediment yield that might occur as a result of a given activity. These issues can be divided into two basic categories--on-site issues and off-site issues. The term "on-site" refers to those issues that are pertinent at the point where precipitation--the fuel that sustains the hydrologic cycle--first reaches the surface. The "off-site" terminology refers to those issues that are pertinent to the disposition of the precipitation and resulting streamflow.

In order to objectively evaluate potential impacts, the concept of levels of evaluation or analysis is introduced. Three levels are defined. They include (Figure 2): Atmospheric Level, Precipitation Level, and River or Streamflow Level.

Atmospheric Level

The atmospheric is perhaps the most important evaluation level, since it deals with the precipitation process itself. However, evaluation at this level generally is not a requirement for evaluating impacts on water and sediment yield. The sophisticated systems needed to collect and analyze atmospheric data require a large investment of money, time, and skills. Accordingly, knowledge of atmospheric or cloud physics has not entirely kept up with the need to determine the basic processes that might be affected by mining activities not directly related to water and sediment yields.

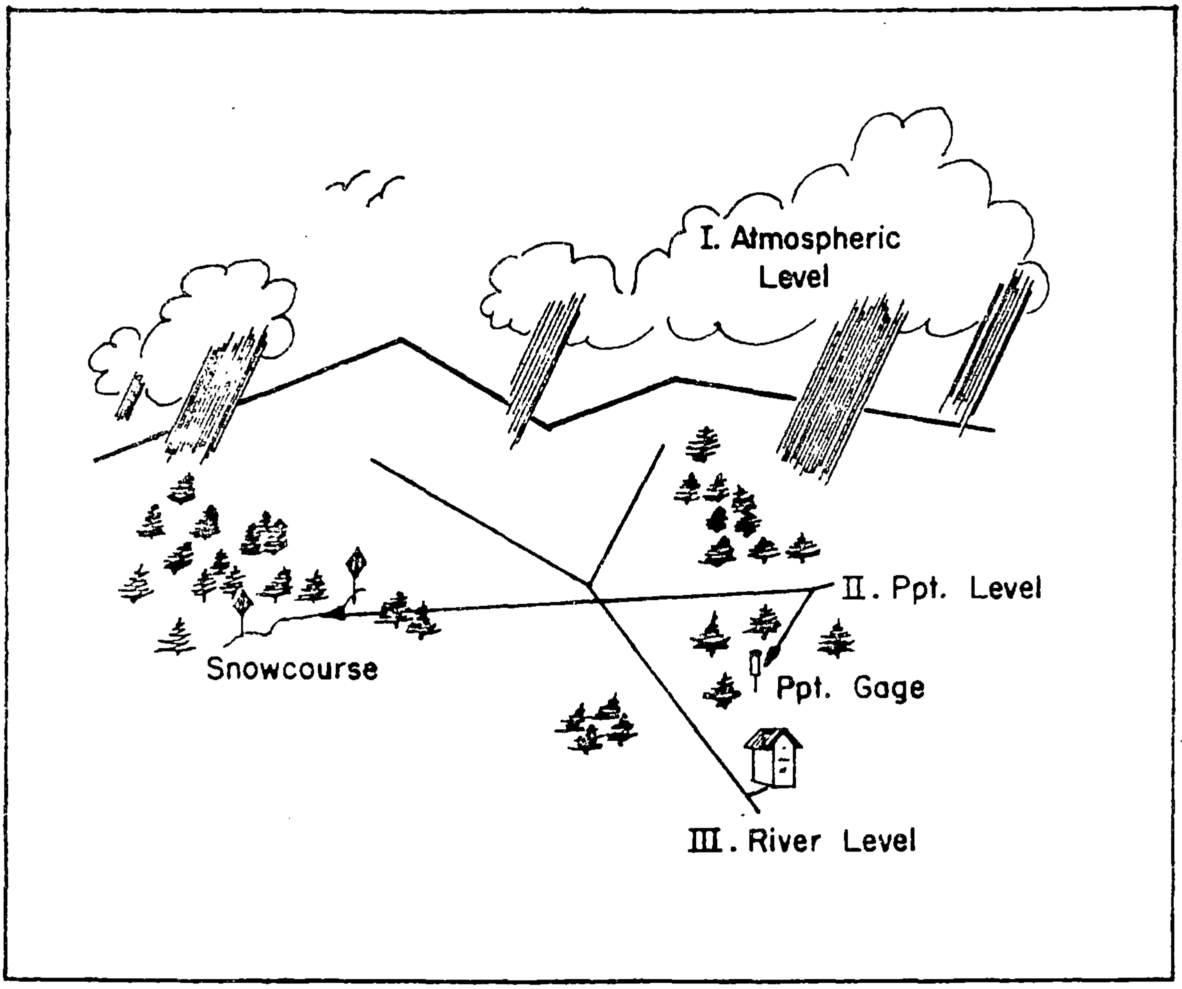


Figure 2.--**Schematic diagram of levels for evaluation** (Markovic, 1966).

Precipitation Level

The precipitation level is most widely used in water-related impact evaluations, because it is at this level where many issues become important. One of the serious shortcomings of analyses at this level, however, is the lack of accuracy in most precipitation measurements. Again, it is at this level that the on-site impacts of mining activities become pertinent.

River Level

From the standpoint of water resources, the river level is extremely important, since the hydrograph is the integral result of the energy, precipitation, and soil-plant-water interactions on the basin. Moreover, consideration of such issues as water quality and fluvial geomorpholgy must be at this level.

Issues and Associated Factors

Issues themselves are important, but without due consideration of the associated factors or dynamic processes, they become meaningless if impacts are to be quantified. Thus, some of the more important factors associated with various issues were also identified. These issues and associated processes are summarized by on-site and off-site categories (Levels II and III) as they are influenced by natural resource development in Table 1.

Table 1.--On-site (Level II) and off-site (Level III) issues with associated factors that are pertinent to the determination of impacts

On-Site	Off-Site
A. Erosion (water)	A. Water Quality
1. Surface	1. Physical
2. Mass wasting*	2. Chemical*
	3. Biological*
B. Microclimate	B. Fluvial Geomorphology
1. Air Temperature	1. Channel Processes
2. Soil Temperature	2. Sediment Yield
3. Snow Cover Amount and Duration	
4. Soil Moisture	
5. Surface Humidity	
6. Radiation Balance	
7. Consumptive Use	
C. Water Yield	
1. Quantity	
2. Distribution	
3. Slope Hydrology*	

*not explicitly considered in these guidelines

Analytical Framework

In order to recognize and quantify impacts on erosion and sediment yield, a concise interactive framework for analysis must be developed, as for example, that presented in Figure 3.

Figure 3 shows all of the major analysis components pertinent to the hydrologic system and their relationship with one another. The type of line used to connect the analysis components depicts a subjective assessment of the degree of understanding of the linkage between analysis components.

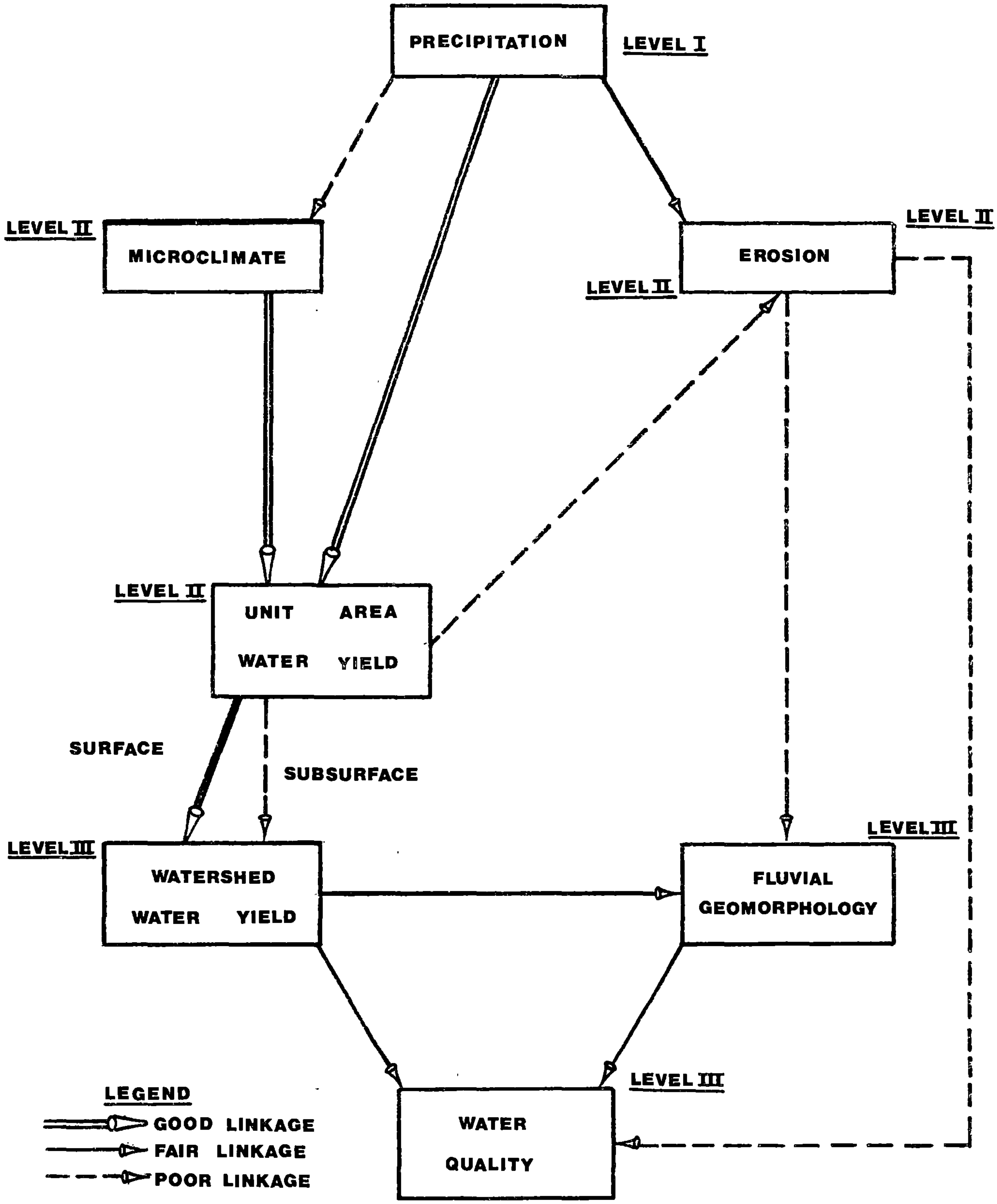


Figure 3.--Flow chart showing analytical framework. (Adapted from Proceedings Skywater Conference IX)

In this chapter, each component of the analytical framework will be discussed in terms of its primary elements, what the outputs of the analysis are, and in general terms, the current technology that is available for quantifying the outputs.

Identification of the linkages between components is a must if one is to adequately address specific environmental issues as well as the interdependency of these issues.

Level I

Precipitation

Precipitation drives the hydrologic system and is the atmospheric water reaching the surface as rain or snow. Our understanding of the linkages between Levels I and II vary from good to poor as seen in Figure 3.

Level II

Microclimate

Microclimate pertains to on-site factors such as temperature, moisture, and radiation characteristics. In the Rocky Mountain/Inland Intermountain Region, the direct effects from mining activities are on hydrologic processes such as snowmelt, evapotranspiration, and soil moisture. Secondary effects may concern such processes as air temperature, soil temperature, surface humidity, and the radiation balance.

Outputs include such factors as the time increment temperatures, consumptive use rates, moisture levels, radiation fluxes, and depth/duration of snow cover.

As seen in Figure 3, the linkage between microclimate and unit area or on-site water yield is relatively well developed.

Erosion

The primary concerns of mining activities as far as this issue is concerned have to do with surface erosion (detachment and movement of soil particles) and mass wasting (slumps, slips, earth and mudflows, debris slides, etc.) Erosion is determined by the amount and intensity of precipitation that strikes the land surface. Precipitation is the primary agent for detachment and transport by runoff resulting from rainfall or snowmelt. Freeze/thaw cycles also affect detachability. Mass wasting, etc. is affected by any change in vegetation and soil/water status which determine shear strength. Freeze/thaw cycles affect dry ravel and rock movement.

Outputs from the erosion process include the amount of surface material that is made available for transport into stream channels. As discussed later in these guidelines, these outputs are needed as inputs into fluvial geomorphic analysis and water quality (physical and chemical elements).

As also discussed in these guidelines, current understanding of the delivery of eroded material to channel systems is poor. Coefficients for delivery are usually subjective estimates, and regression techniques are commonly used to derive these parameters.

Level III

Unit Area Water Yield

The unit area water yield component includes the water balance analysis that results in estimating on-site water available for streamflow. This water is subsequently routed through surface and subsurface pathways to the streams.

The impacts of mining activities on precipitation and microclimate must be estimated before impacts on unit area water yield can be determined. Our understanding of the linkages between these components is good. However, the linkages between unit area water yield and watershed water yield (routed streamflow) is good to poor depending on whether routing is surface or subsurface.

Fluvial Geomorphology

Fluvial geomorphology is concerned with channel processes (channel erosion and bed material redistribution), and sediment yield, or the output from upland and channel sources. The primary effects of mining activities on channel processes relate to streamflow duration, peak flow, and quantity. Sediment yield is dependent on the impact that mining might have on both erosion and channel processes. Outputs consist of the amount of sediment available from channel sources that affect physical water quality and the contributions of sediment from channel sources available for depleting water storage and conveyance systems capacity. As seen in Figure 3, the linkage between erosion and fluvial geomorphology is poor, whereas our understanding of the linkages between watershed water yield, fluvial geomorphology, and water quality is fair.

Water Quality

Water quality pertains to the physical, chemical, and biological characteristics of streams, lakes, and aquifers. Physical water quality (sediment) is affected by mining through the direct introduction of point and non-point source effluents, and through changes in streamside and upland vegetation, streamflow quantity and timing, lake levels, and aquifer recharge rates. Because the physical characteristics of water are flow dependent, unit area and watershed water yield must first be quantified before impacts on water quality can be determined.

Outputs from the water quality component include physical, chemical, and biological characteristics of marshes, streams, lakes and aquifers.

Water quality characteristics are extremely important inputs to primary biological systems (fisheries, etc.). "Loading functions" or rating curves for water quality characteristics are needed as inputs to this analysis component. These best describe physical phenomena such as channel processes, and are weakest in defining the chemical and biological processes. Empirical loading functions are currently being developed that allow comparative analyses of water quality, but they are deficient in accurately assessing the significance of any changes on biological water quality. As seen in Figure 3, the linkage between erosion and water quality is poor.

CHAPTER 2

EROSION

Erosional wastes generated from mining activities are often a significant part of the non-point source pollution problem. Accordingly, even approximate quantification of on-site erosion and delivery of detached material is essential. Roads, benches, mine spoils embankments, etc. are all primary eroding surfaces in subalpine areas, as elsewhere.

In order to adequately quantify on-site erosion, it is important that these areas be adequately defined as to location, engineering design criteria, and soil properties. Moreover, the natural (baseline) forest environment must also be examined in order to evaluate the erosive energies and susceptibility of the land surface to erosion.

On-site erosion is intimately associated with the water cycle in that material is first detached from the surface by rainfall, and subsequently transported to streams by runoff associated with both snowmelt and rainfall. Typically, soil materials are detached from eroding surfaces by rainfall, transported some distance to concentration points, and subsequently carried to streams principally during the snowmelt runoff season. Upland erosion and delivery is complex, since it may take several runoff seasons before detached soil materials are ultimately discharged from the watershed through an assortment of non-steady state processes.

Status of Knowledge in Quantifying On-Site Erosion

Ideally, quantification of surface erosion should be based on process-oriented models. However, few if any are available. Recently, Simons and Li (1975) developed a process-oriented simulation model for sheet erosion which apparently gives reasonable results provided that the user has the necessary detailed site specific information and a large computer at his disposal.

Because process simulation models are not yet readily available, empirical approaches must still be relied upon for most applied work. Numerous such approaches have been developed, and many of these are summarized in the proceedings of a recent workshop at the USDA Sedimentation Laboratory (USDA, 1975).

Of the several available empirical formulations, perhaps the so-called "Universal Soil Loss Equation" (Wischmeier and Smith, 1965), is best known and most widely used. Recently, this equation and associated methodology has been adapted for use in wildland settings for the Transportation Research Board of the National Research Council by the Utah Water Research Laboratory, Utah State University, and the Intermountain Forest and Range Experiment Station (Utah Water Research Laboratory, 1976). This project extended the mapped values of R and K to the Western United States and developed procedures for applying the USLE to highway construction. This procedure is recommended herein as currently being the most adequate for use in evaluating on-site erosion from mining activities. The objectives of these guidelines are to propose methods for evaluating the impacts of mining on non-point source pollution from some baseline condition. Essentially, the modified USLE has been designed for use "as a predictive tool and risk evaluator", which conforms to the objectives of this report.

Modified USLE

The following discussion of the modified USLE has been excerpted from Volume II of the Utah Water Research Laboratory project (Project 16-3). This procedure is proposed for use during any time interval from a single storm event of any specified recurrence interval to annual totals. The USLE and discussion of its modifications and limitations are briefly summarized below; details are presented in Appendix I.

In its simplest form, the USLE is expressed as follows:

$$A = RKLSVM \qquad [1]$$

in which

- A = computed amount of such soil loss per unit area for the time interval represented by the rainfall factor R, generally expressed as tons/acre/yr.
- R = rainfall factor,
- K = soil erodibility factor,
- LS = topographic factor (length and steepness of slope), and
- VM = erosion control factor (vegetative and mechanical measures).

Rainfall Factor R

The rainfall factor is the number of erosion index units in a normal year's rain. The erosion index is a measure of the erosive force of specific rainfall, and is defined for a single storm as:

$$R = \frac{EI}{100} \qquad [2]$$

in which

- E = the total kinetic energy of a given storm in ft-tons/acre
- I = the maximum 30-minute rainfall intensity for the area in inches per hour at whatever recurrence interval is chosen for A.

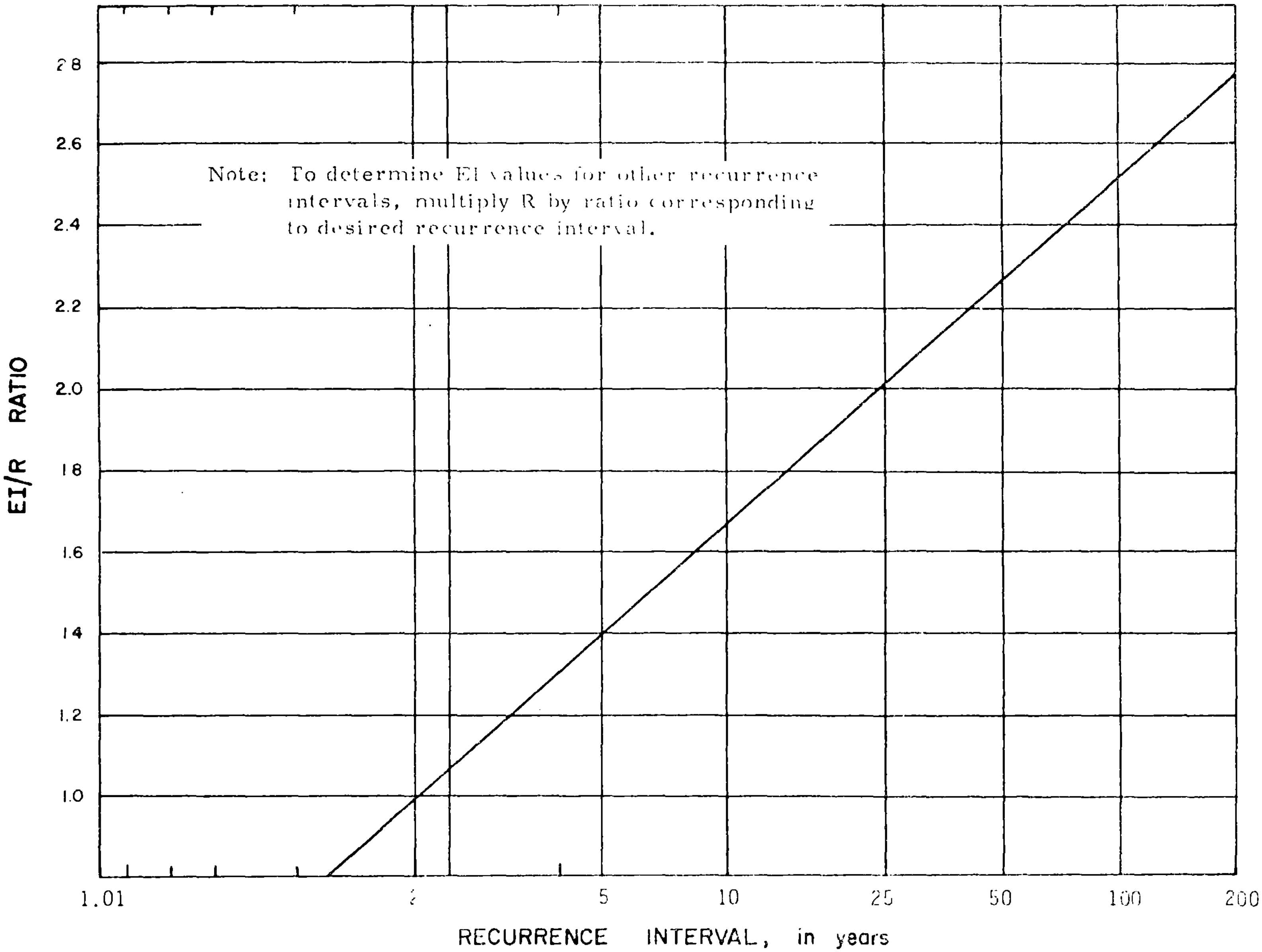


Figure 4. The relation between the EI/R ratio and recurrence interval.
(Utah Water Research Laboratory, 1976)

The rainfall factor, R, is computed from rainfall records of individual storms and summed over a given time interval to obtain the cumulative R value for an average year (2.2-year recurrence interval), to be used in equation [1]. Values of EI/R for recurrence intervals other than 2.2 years are plotted in Figure 4. R is derived from probability statistics and should not be considered as a precise estimator of soil loss. As emphasized in Volume II (Utah Water Research Laboratory, 1976), the value of R lies in its use as a predictive tool and risk evaluator. Obviously, mining activities in areas with high values of R will require greater attention to erosion control practices than similar activities in areas of low R values.

In the absence of local rainfall data, annual R values can be determined from maps developed by Project 16-3 (Appendix I).

R values can also be determined for periods of less than 1 year, using maps reproduced from Project 1603 (Appendix I). These maps are very general, and therefore may not be strictly applicable to local conditions. A preferable approach in lieu of using the maps would be to distribute R based on the distribution of the erosive energy of runoff events throughout the year as determined from a local hydrologic analysis.

Soil Erodibility Factor, K (Figure 5)

The soil erodibility factor, K, is a numeric representation of the ability of the soil to resist the erosive energy of rainfall. Large values of K denote highly erodible soils. The soil erodibility factor is independent of slope and dependent only upon particle size and distribution, structure, void space and pore size, and organic matter. The baseline situation for this factor is soil in a natural unconsolidated state.

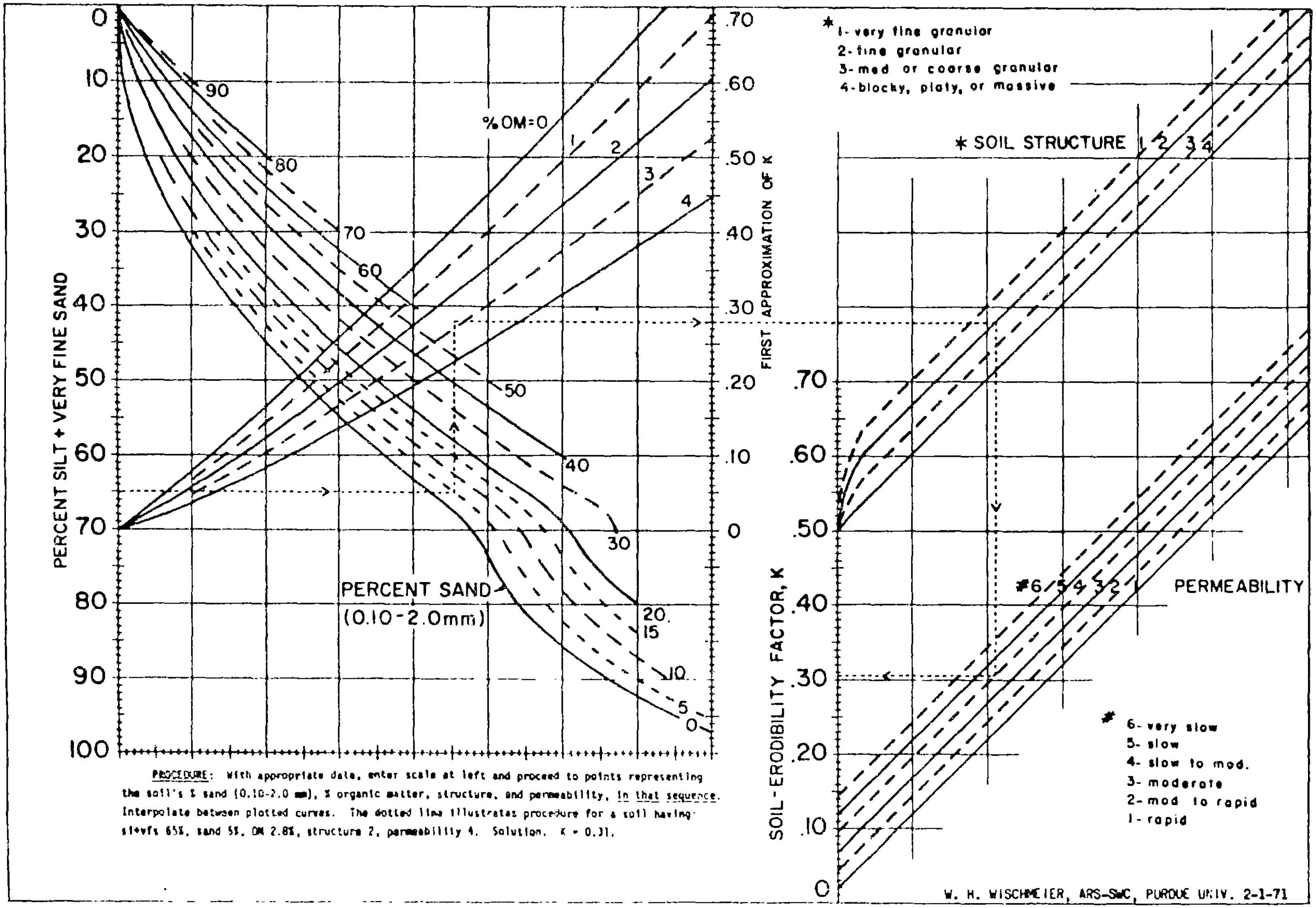


Figure 5. Nomograph for determining soil erodibility factor K, (Utah Water Research Laboratory, 1976).

Mechanical alterations of the soil through blading, compacting, etc. which change its structure are accounted for in the soil loss equation by the VM factor which is discussed later. The procedure for determining K is discussed in Appendix I. A map of soil erodibility produced by Project 16-3 can be used if local data are not available.

Topographic Factor, LS

Adjustments to the USLE which reflect disturbance are possible through manipulating the topographic factor, LS and the erosion control factor, VM. The rainfall factor, R, and soil erodibility factor, K, have both been fixed by nature and cannot be altered appreciably by mining. The steepness and length of many of the slopes in such earth structures as roads, benches, and mine waste embankments, however, are determined by the engineer after consideration of the physical setting of the watershed and the factors listed at the beginning of this discussion.

Obviously, flat slopes and short lengths will experience less erosion than steep slopes and long lengths, but the amount of erosion expected for various combinations of length and steepness is not readily apparent. The LS factor is therefore a numerical representation of the length-steepness combination, which, when multiplied by R and K will give the potential erosion from a given slope. Because slope and slope length are determined by the designer, an understanding of the LS factor will aid him in selecting proper combinations of these variables, and determining when to use control practices which effectively reduce the LS factor, and thus surface erosion.

A basic equation has been proposed by Project 16-3 for estimating the topographic factor as follows:

$$LS = \left(\frac{0.43 + 0.3s + 0.043s^2}{6.613}\right)\left(\frac{\lambda}{72.6}\right)\left(\frac{10,000}{10,000+s^2}\right) \qquad [3]$$

in which LS = topographic factor

λ = slope length in feet

s = slope steepness in percent

m = exponent dependent upon slope steepness (0.3 for slopes < 0.5%, 0.5 for slopes 0.5% to 10%, 0.6 for slopes > 10%).

Computational procedures developed by Project 16-3 enable the designer to determine an LS factor for virtually all combinations of single and multiple slopes encountered in mining. These procedures are presented in Appendix I.

Erosion Control Factor, VM

The erosion control factor is an all-inclusive parameter. It accounts for the effects of all erosion control measures that may be implemented, including vegetation, mechanical treatment of the soil surface, chemical treatments, etc. It does not include structural controls such as benches, since these are part of the topographic factor, previously discussed. For any site, the USLE can be used to estimate soil loss with and without erosion control. This procedure enables one to determine the relative effectiveness of a given control in reducing soil loss. Appendix I contains procedures for estimating VM factors for various control methods.

Sediment Delivery

The procedures discussed above enable quantification of on-site erosion. In order to determine the impacts of this erosion on water quality, something must be known about the processes which deliver the detached soil to streams. These processes have generally been lumped into one parameter defined as the "delivery ratio". This ratio is expressed as the amount of erosion yielded at a reference point in a stream divided by the upland gross erosion (sediment yield/gross erosion). Hence, in its simplest terms, sediment yield = gross erosion x delivery ratio.

Normally, sediment yields have been determined from accumulations in debris basins or reservoirs. Relationships between delivery ratio and drainage area have been derived from these data. One such relationship is shown in Figure 6. More detailed information on empirically-derived delivery ratios is available in a handbook recently published by the American Society of Civil Engineers (ASCE, 1975).

Perhaps the most important and weakest link in the non-point source area has to do with estimating sediment delivery. While considerable data exist for such areas as the midwestern and southeastern portions of the United States, little if any reliable information is available from subalpine areas--particularly in the Rocky Mountain/Inland Intermountain Region.

Accordingly, relationships such as that shown in Figure 6 may not accurately reflect delivery in the subalpine zone.

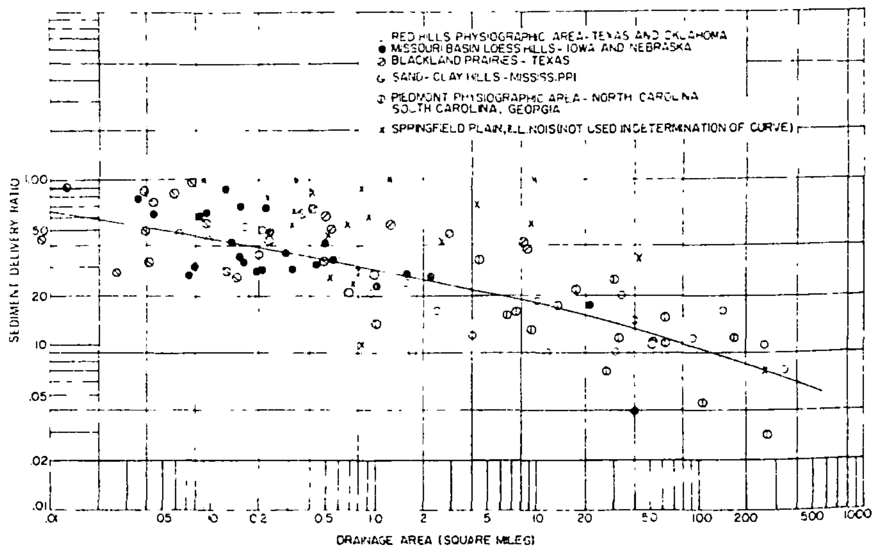


FIG 6.—Relationship between Size of Drainage Basin and Sediment Delivery Ratio (ASCE, 1975).

Currently, an innovative procedure for computing the delivery ratio is being developed by the U.S. Forest Service Watershed Systems Development Unit in Fort Collins, Colorado.[3/] This procedure is based on the assumption that delivery can be expressed as:

$$D_{rax} = (D_{rSax})(D_{rVax})(D_{rRax})(D_{rKax})(D_{rDax}) \qquad [4]$$

in which D_{rax} = the delivery ratio used to adjust potential soil loss

D_{rSax} = the effect of slope on delivery

D_{rVax} = the effect of ground cover on delivery (including vegetation, mulch, rock, etc.)

D_{rRax} = the effect of rainfall intensity on delivery

D_{rKax} = the effect of soil particle size on delivery

D_{rDax} = the effect of distance on delivery where the eroding surface does not border a natural or artificial drainage way.

As seen in equation [4], the factors are assumed to be independent and multiplicative in their combined relationship to total delivery. The mathematical formulation of these factors expressed as functions of the various variables (slope, rainfall, etc.) are based on the Simons-Li model for surface erosion (Simons-Li, 1975).

Current research in the area of delivery promises to generate more objective and process-oriented techniques for estimating delivery ratio. However, until these methods are better developed, most applied work in the subalpine zone must rely on the few documented watershed studies for this type of information.

[3/] Personal correspondence with Mr. Kerry Knapp, Hydrologist, WSDU, Fort Collins, Colorado.

The effects of logging and logging roads on erosion and sediment yields reported by Megahan and Kidd (1972) and Leaf (1970) provide at least some data that are pertinent to mining activities. Megahan and Kidd (1972) found that logging operations exclusive of roads increased sediment yields by a factor of about 0.6 over baseline levels, whereas jammer logging roads increased yields 750 times in a 6-year period following construction. In central Colorado, Leaf (1970) reported at least a two-fold increase in sediment yields in the years during and immediately following road construction and logging.

Megahan (1974) and Leaf (1974) have shown that sediment yields increase subsequent to logging, but decrease in later years toward a regime which can approach preharvest levels. This response can be expressed as a negative exponential equation with a linear component containing three parameters to describe the time trends in erosion discussed above. For a first order watershed, the equation can be expressed as:

$$E = \varepsilon_n t + S_o(1 - e^{-kt}) \qquad [5]$$

where

E = the cumulative on-site erosion at time (t) after disturbance,

ε_n = an estimate of the long-term baseline unit sediment yield,

S_o = an index of the total amount of soil delivered to the stream from disturbed areas, and

k = an index of the rate of decline of erosion following disturbance.

The parameter, (ε_n) is the long-term erosion "norm" which is reestablished after a site is disturbed. In some areas, this new norm may be higher than the long-term erosion under natural conditions because of irreversible changes in site factors.

Solution of equation [5] in combination with the USLE discussed above is proposed for use in these guidelines as being a first-order approximation of the amount of sediment introduced to the stream over a period of years following disturbance. The procedure is discussed below.

Briefly, the proposed method assumes a first-order watershed and an input/output model in which upland erosion and delivery under baseline conditions is given by the equation:

$$\varepsilon_n \approx D_r \cdot A_b; \; D_r = \frac{\varepsilon_n}{A_b} \qquad [6]$$

in which ε_n = baseline unit sediment yield as discussed in equation [5]

D_r = delivery ratio, and

A_b = annual unit on-site baseline erosion computed by the USLE discussed above (equation [1].

Equation [6] is a conservative estimate for D_r since at least part of the sediment yield (ε_n) is derived from channel erosion.

The baseline unit sediment yield (ε_n) is determined from field data through continuous measurements of suspended sediment, bedload, and streamflow, and/or from seasonal measurements of trapped sediment in debris basins.

The second term (S_o) in equation [5] is an index of the total amount of material that is delivered to the stream over a period of several years following disturbance by mining activities. An index of this quantity is given by the equation:

$$S_o = D_r \cdot R \cdot K \cdot LS(VM_1 + VM_2 + VM_3 + \dots VM_n) \qquad [7]$$

in which $R \cdot K \cdot LS$ = potential unit on-site erosion computed from equation [1] after disturbance, and

$VM_{1 \dots n}$ = erosion control factors (equation [1]) each year following treatment.

Generally, highest yields occur soon after disturbance and taper off in subsequent years to a new norm. In central Colorado, this norm was reached in approximately 7 years (Leaf, 1974). The erosion control factors will vary from year to year, depending upon the mining activity and controls employed to reduce erosion. The parameter, (k), in equation [5] depends on local geology, hydrology, and soils, as well as the controls used to reduce erosion. In central Colorado, k $\approx$ 0.085 (Leaf, 1975).

CHAPTER 3

CHANNEL PROCESSES

It is obvious that changes in forest cover and soil disturbance associated with mining activities can also produce changes in streamflow quantity, timing, and water quality. However, the impacts from mining on the channel systems that convey this water may not be so obvious. Accordingly, these guidelines also discuss methods for estimating:

1. The contribution of channel-derived sediments either from scour or redistribution of previously deposited sediment.
2. Impacts on dynamic channel equilibria resulting from the direct introduction of sediment and from channel disturbances.

Stable Channel Balance

Lane (1955) has shown that in any stream there exists a dynamic equilibrium which can be expressed as:

$$(\text{sediment load}) \times (\text{sediment size}) \propto (\text{stream slope}) \times (\text{discharge})$$

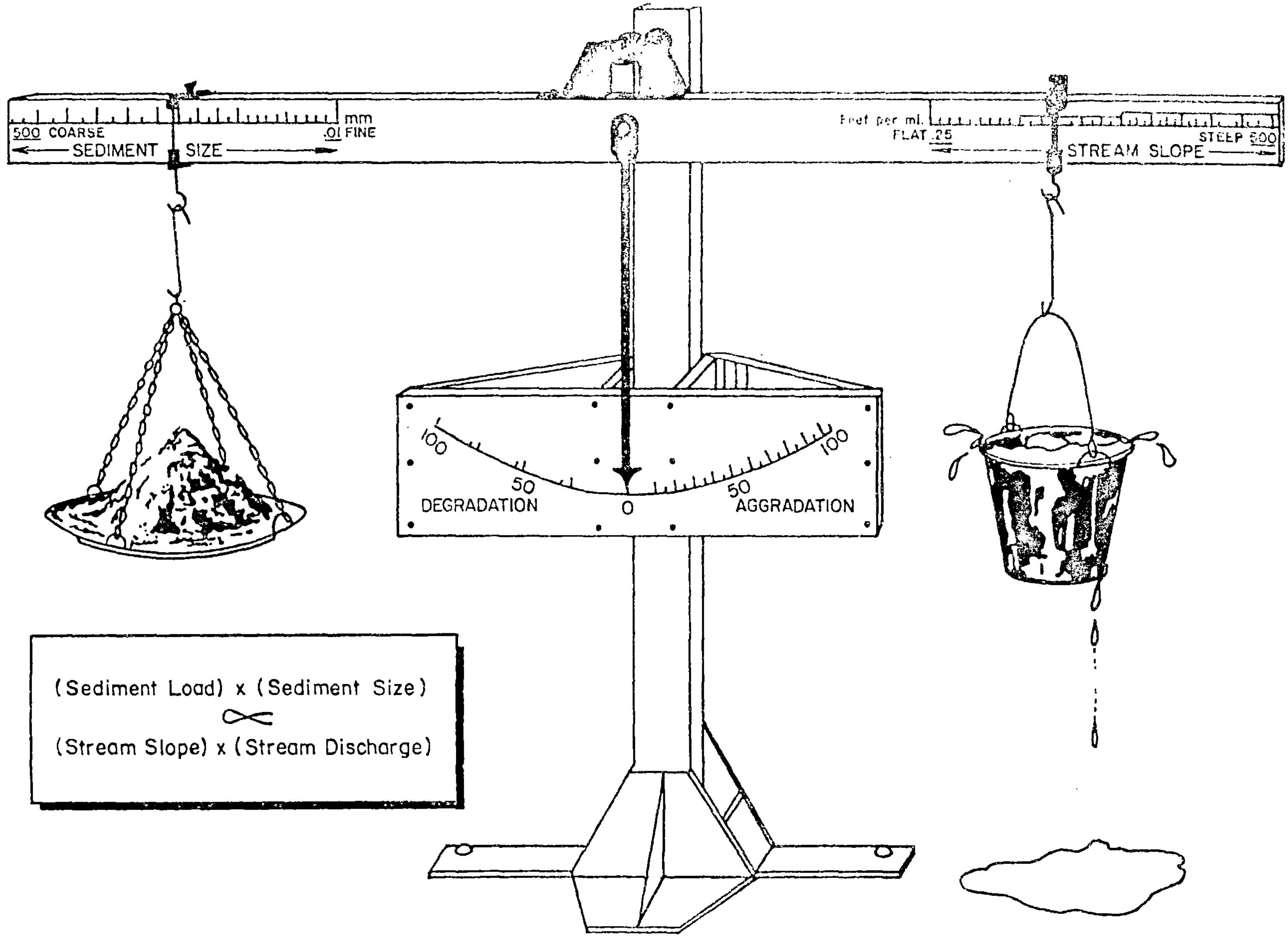
A change in one or more components will disrupt this balance or equilibrium. Once the equation has been changed, the stream will readjust itself in order to regain a new equilibrium. Such readjustments are important to man and his activities.

The equation above can be well illustrated by Figure 7. As seen in this figure, the delivery of additional sediment will cause a stream in equilibrium, all other things being equal, to aggrade. Likewise, if only the size of sediment is increased, the stream will also aggrade. Increases in runoff or channel slope will both cause the stream to scour or degrade. Figure 7 denotes a sensitive balance which must be considered whenever a subalpine watershed is subjected to appreciable disturbance.

Sediment Rating Curves

Basic relationships which define channel stability and sediment yield are sediment rating curves (Rosgen, 1975). Examples of such curves are shown in Figures 8 and 9. These curves are rated from excellent channel stability to very poor. The stability of stream channels varies by hydrologic and physiographic setting and from reach to reach in a given watershed. Interpretation of this variability is necessary for assessing sediment sources due to channel processes. One such characterization was developed by Pfankuch (U.S. Forest Service, 1975). Its use by Forest Service hydrologists has shown this system to be a reliable and objective means for interpreting rating curves (U.S. Forest Service, 1975). The channel rating system is included as Appendix III in these guidelines.

The analysis of channel processes involves stability rating determinations of a given stream channel reach using procedures set forth in Appendix III. Suspended sediment concentrations and stream discharge are also obtained for a wide range of streamflow conditions. These data are then plotted on log-log paper. The resulting regression line has an equation of the form:



STABLE CHANNEL BALANCE

Fig. 7.—Stable channel balance (after Lane, 1955)

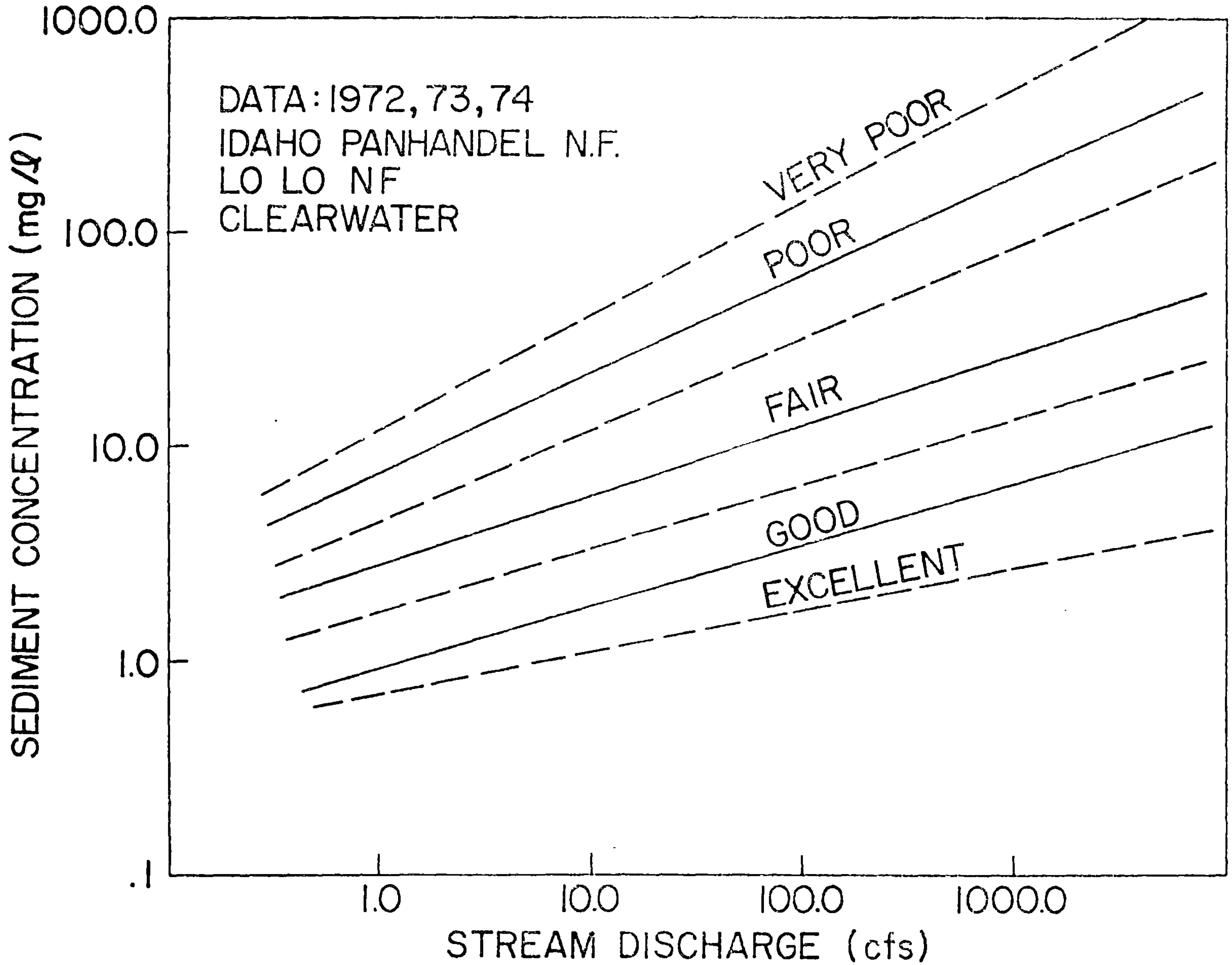


Fig. 8.--Sediment rating curve by [illegible] stability [illegible] (Rosgen, 1975)

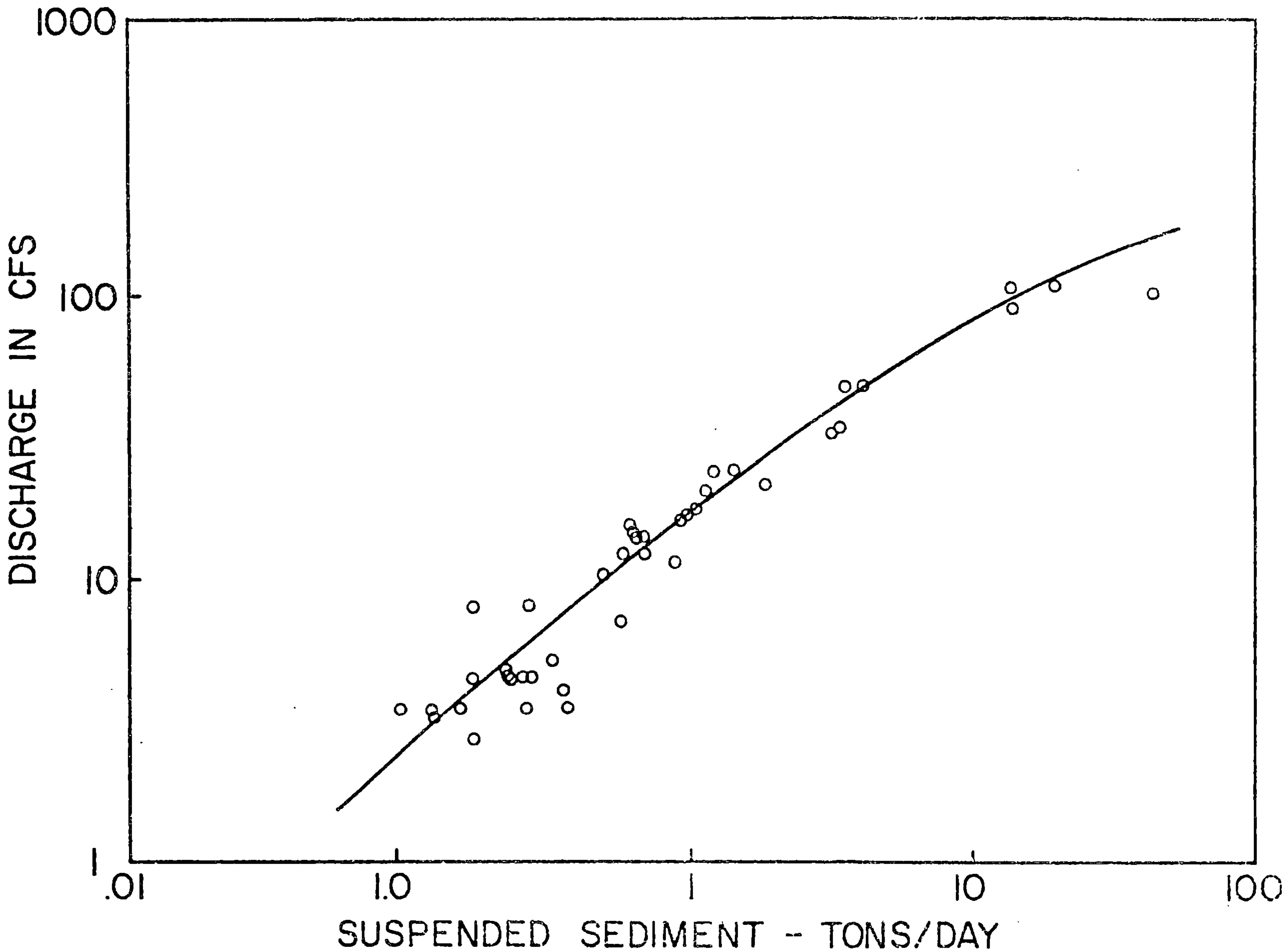


Fig. 9.-Station: 01.01 North Fork Lower Willow Creek above [illegible]
(Farnes, 1975)

$$Y = bQ^n \qquad [8]$$

in which Y = sediment concentration in mg/l,

b = a constant (intercept),

Q = stream discharge in cubic feet per second,

n = an exponent (representing slope).

According to Rosgen (1977), ". . . this simple regression has produced good correlations throughout the United States that are significant when comparing representative flows for a given year to actual concentrations for those flows. . ."

Because streamflow is the primary transporting agent, watershed disturbances that change the quantity of flow or its timing will cause channel adjustments to occur. The direct introduction of sediment may also cause the rating curve to "shift" to a lower stability category, with associated undesirable channel adjustments.

To date, enough sediment rating curves have been constructed for streams throughout the Western United States so that "morphological characterizations of stream channels through stability analysis can be used to quantify channel erosion and sediment transport where sediment data are not readily available . . ." (Rosgen, 1977). This result suggests that channel stability ratings on undisturbed watersheds can provide first approximations of baseline sediment yields (ε_n) previously discussed.

Impacts from Introduced Sediment

Sediment rating curves are empirical; therefore, a confidence interval can be drawn above and below the regression line. One criteria for determining if a given stream is capable of transporting introduced sediment is the upper confidence band. If the introduced sediment results in concentrations (yields) that plot outside of the band, then in all likelihood, the carrying capacity (competence) will be exceeded and the stream will readjust itself through lateral migration and aggradation. Estimates of the amount of introduced sediment can be made using procedures discussed in Chapter 2.

Bedload Transport

Bedload is difficult to measure directly; however, an indirect procedure for determining bedload transport has recently been developed by Leopold and Emmett (1976). This procedure utilizes a general empirical relationship between unit stream power and the size of material being transported. The relationships are shown in Figures 10 and 11. To use these curves, field measurements of average bed material size on channel bars below bankful stage are required (Rosgen, 1976). Unit stream power, which is a function of discharge, channel geometry, and gradeline can be computed by the equation (Leopold et al., 1964):

$$\omega = \frac{\rho_\omega g Q s}{W} \qquad [9]$$

in which ω = stream power per unit width,

ρ_ω = mass density of the flowing water,

g = acceleration of gravity

Q = discharge,

s = slope of the energy gradeline, and

W = channel width.

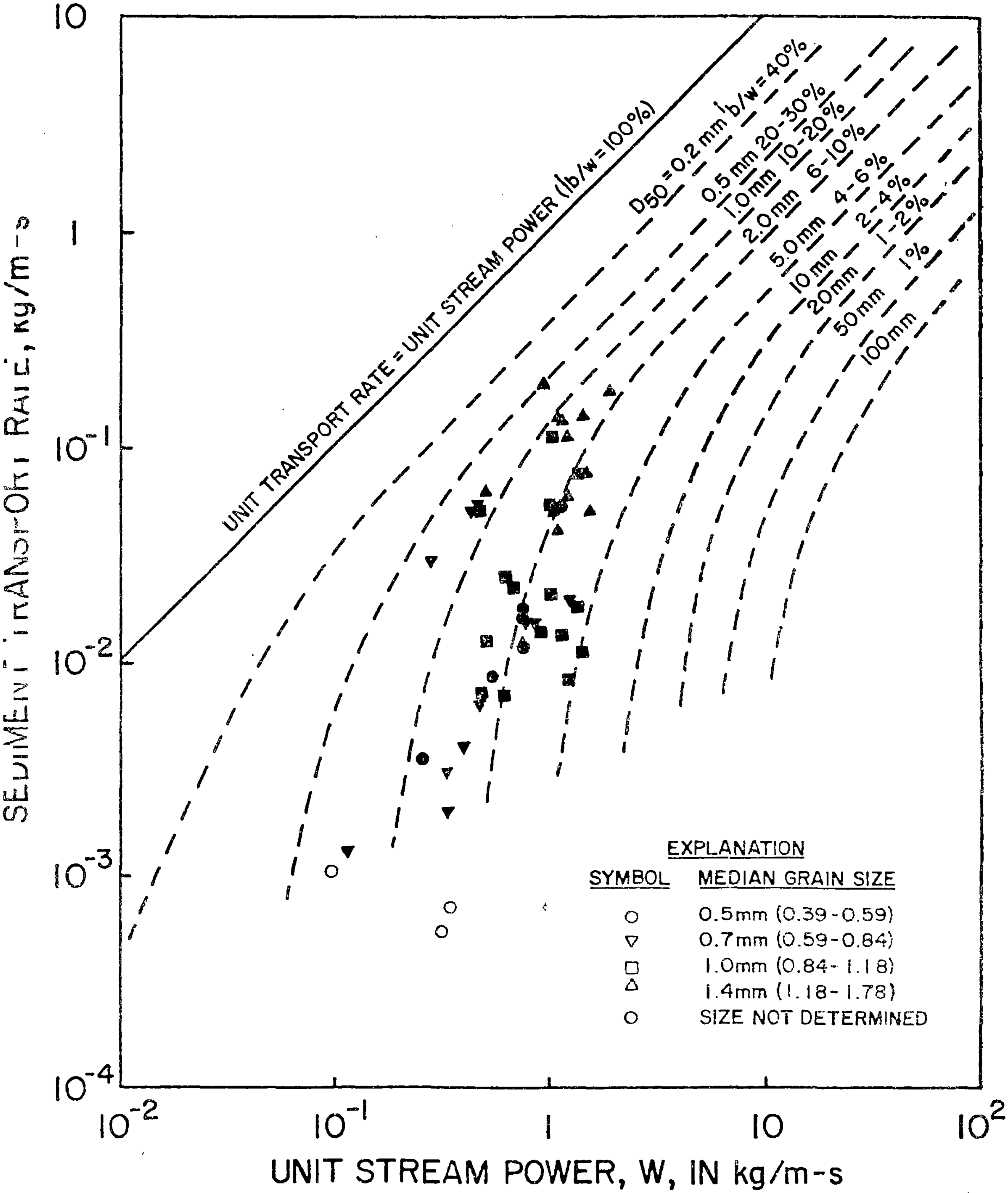


Fig. 10.--Sediment transport rate (bed load) as a function of unit stream power. (Leopold and Emmett, 1976)

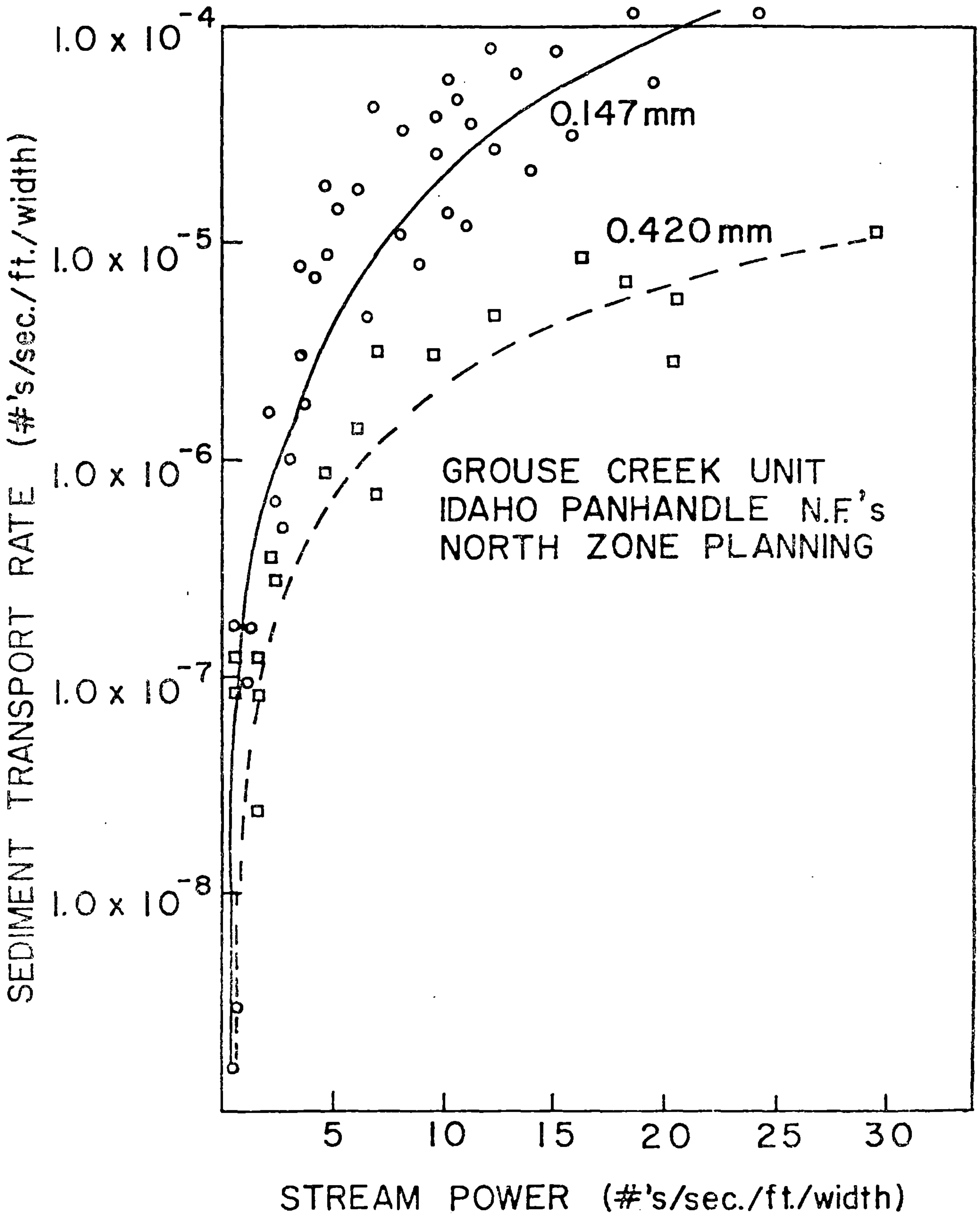


Fig. 11.-Bedload transport rates/stream power/size. (Rosgen, 1975)

In English units, equation [9] can be written as:

$$\omega = \frac{\gamma Qs}{W} \qquad [10]$$

in which ω = unit stream power in ft-lb/sec,

λ = specific weight of water in lb/ft^3, and

W = width in ft.

As seen in Figures 10 and 11, appreciable changes in flow regime, size of bed material, and hydraulic gradeline (through encroachment or channelization, for example), all will affect bedload transport, and thus the dynamic equilibrium of the stream.

CHAPTER 4

HYDROLOGY

The hydrologic cycle is the core system that determines both on-site (Levell II) and channel (Level III) processes (Figure 2). Accurate information on local hydrologic conditions at both the II and III levels is a must for rational assessments of impact. This chapter briefly describes the hydrology of the Rocky Mountain/Inland Intermountain Subalpine Zone. Basic hydrologic processes affected by forest cover removal are next discussed in some detail. Finally, application of a hydroloqic simulation model is discussed, and procedures are proposed for utilizing regional response relationships generated from this model for evaluating hydrologic impacts from mining activities.

Regional Hydrologic Characteristics

Research watersheds have provided us with considerable information about the hydrology of the subalpine zone. Some significant findings from the classic Wagon Wheel Gap experiment (Bates and Henry, 1928) were:

- Little, if any, overland flow of water appeared at any season, and the quantity of eroded soil was small.
- Mean annual temperature did not exceed 35°F, and mean annual precipitation was approximately 20 inches.
- Total precipitation was about half snow and half rain. With the exception of south slopes, there was no snowmelt during winter until after early March.

- Of the total precipitation, about one-half is stored in winter snow accumulation and is released during the spring melting period.
- More than 55 percent of the total streamflow occurred from April through June.
- The difference between precipitation and runoff indicated evaporation is a fairly constant 15 inches annually.

Water-balance studies at the Fraser Experimental Forest have also given us insight into the hydrology of spruce-fir and lodgepole pine forests. In developing operational runoff forecasting methods, Garstka et al. (1958) found that water yield is 45 to 55 percent of the annual precipitation. Of this amount, 90 to 95 percent is derived from snowmelt. Typically, winter conditions keep the snowpack well below freezing until late March or April. Peak seasonal snow accumulation averages 15 inches of water equivalent, and during the melt season, the depleting snowpack is augmented by more than 5 additional inches of precipitation. Subsequent rainfall during the summer and early fall averages 8 to 10 inches. Thus, of this 28- to 30-inch input, about 12 to 15 inches becomes streamflow.

The above discussion is a good general account of hydrologic conditions in the Rocky Mountain/Inland Intermountain subalpine zone, except that melting begins later in the spring in the more northern part of the region and there are areas that receive more precipitation. For example, in the Park Range in Colorado, the Beartooth Mountains in Montana, annual precipitation can exceed 50 to 65 inches, and water yields average 25 to 45 inches. Mean annual water balances for representative watersheds are summarized in Table 2.

Table 2.--Mean annual water balances (inches) for typical subalpine watersheds in the Rocky Mountain/Inland Intermountain Region

Watershed	Seasonal snowpack, water equivalent	Pre-cipi-tation	Evapo-tran-spira-tion	Runoff
COLORADO:				
Soda Creek, Routt NF	42.6	55.2	16.7	38.5
Fraser River, Arapaho NF	15.0	30.3	16.9	13.4
Wolf Creek, San Juan NF	26.2	48.0	21.0	27.0
Trinchera Creek, Sangre de Cristo Mountains	9.5	19.6	14.5	5.1
WYOMING:				
South Tongue River, Bighorn NF	15.5	29.6	15.8	13.8
MONTANA:				
W. Fork Stillwater River, Custer NF	30.1	49.1	17.0	32.1
IDAHO:				
Diamond Creek, Caribou NF	15.2	23.6	14.7	8.9

Basic-Hydrologic Processes Affected by Vegetation Removal

In this section, analytical procedures are identified that can be used to quantify the relative hydrologic changes from subalpine vegetation manipulation associated with mining. These procedures are structured into a framework that allows an evaluation of alternative patterns of logging on the hydrologic cycle. It is believed that the principles set forth in this report are applicable throughout the Rocky Mountain/Inland Intermountain Region. They comprise a logical system which identifies and links vegetation/soil/water relationships and the resultant effect on these dynamic and interactive processes produced by removal of forest cover. This analytical framework is consistent in that the logic can be applied in broad area planning where hydrologic data, activities, and abatement goals are very general, and to specific on-site situations where activities, data, and abatement goals are site specific.

The hydrologic processes are identified as a system of simple mathematical equations. They are expressed in terms of key parameters which define each process. The relationships are general so that the user can quantify each parameter and set limits based on his experience and knowledge of a particular hydrologic regime. Once the parameters have been quantified in terms of the vegetation/soil/water characteristics of a given area, it becomes readily apparent which processes are likely to be modified by mining activities.

Solution of the equations using parameters which describe the natural state will provide the user with an estimate of baseline hydrology. Subsequent solution of the same system of equations using parameters which are altered to define a given treatment will provide the user with an estimate of the hydrologic impact of that particular treatment.

Precipitation

Though simply presented, the "hydrologic equation" encompasses a host of dynamic and interactive bio-physical processes which range from the precipitation that falls on a watershed surface to its ultimate disposition as streamflow. A working knowledge of these processes is a prerequisite to rational evaluation of hydrologic impacts associated with forest cover manipulation.

Vegetation - Terrain Interactions.--Factors that influence precipitation in irregular forest-covered terrain can best be viewed as those related to the atmosphere and those related to the land surface. Atmospheric factors to be considered include airmass characteristics such as precipitable water, stability and temperature characteristics, circulation processes, and precipitation processes. Terrain factors include orientation of the slope to the airmass, upwind barriers to the flow of moisture, elevation of the land surface, and the extent, form, and structure of forest vegetation. Our knowledge of either atmospheric or terrain mechanisms and their interactions is far from satisfactory for quantitative prediction of precipitation. Progress is being made in developing models which give a better insight into the physical processes affecting precipitation regimes. However, until these methods become more developed and are made generally available, the practicing forest hydrologist is forced

to rely on the conventional methods of quantification of areal precipitation from precipitation gage and snow course data.

At a given measurement site, snow accumulation and rainfall can be strongly influenced by wind, which interacts with the gage itself, surrounding vegetation, and local topography. Accordingly, existing networks of snow and precipitation gages can at best give only index values of areal precipitation. When the forest cover is removed as the result of mining activities, precipitation amounts can be changed appreciably - particularly when precipitation falls as snow.

Interception.--Chow (1964) has presented an excellent review of interception processes. Other pertinent references include work by Kittredge (1953), Miller (1964), Satterlund and Haupt (1967), and Sopper and Lull (1967).

Most of the literature dealing with interception is based on field studies in which incoming precipitation is measured at several locations under a forest stand and results compared with measurements in an opening in the same general area. The difference between precipitation amounts in the open and in the forest is then attributed to interception loss.

Merriam (1960) has proposed a general equation for describing the interception processes based on a literature review of rainfall and snowfall data as follows:

$$L = S(1 - e^{-P/S}) + REt_p \qquad [11]$$

where L = the interception loss in inches over the projected area of the forest canopy,

S = the interception storage capacity of the vegetation,

e = the base of natural logarithms,

P = the precipitation during a given storm interval, in inches;

R = the ratio of vegetation surface area to the projected area of the canopy;

E = the evaporation rate in inches depth; and

t_p = time, in hours.

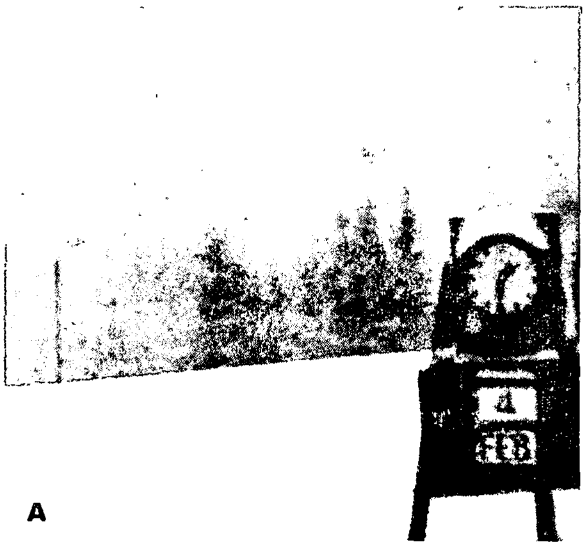
Where snowfall is concerned, comparisons between measurements in forested and open areas can be misleading (Hoover, 1971); accordingly, the forest hydrologist must use considerable judgment in evaluating the effects of forest cutting on interception processes. For example, studies in the Rocky Mountain Subalpine Zone have shown that redistribution of snow is an important phenomenon.

In this region, snow rests on tree canopies only during periods of cloudy weather, low temperature, and frequent snowfall. Typically, after snowfall ceases, wind-generated vortexes and eddies quickly strip the snow from the trees. In a short time this airborne snow is redeposited at varying distances from where it was intercepted (Hoover and Leaf, 1967).

The significance of this phenomenon is illustrated in Figure 12, which shows a time-lapse sequence of a typical snowfall event in central Colorado.

When forest cover is partially removed, interception losses are generally reduced in proportion to the amount of overstory removed. One general equation for snow interception proposed for coniferous trees by Satterlund and Haupt (1967) is given by:

$$I_s = S/\left[1 + e^{-k(P - Po)}\right] \qquad [12]$$



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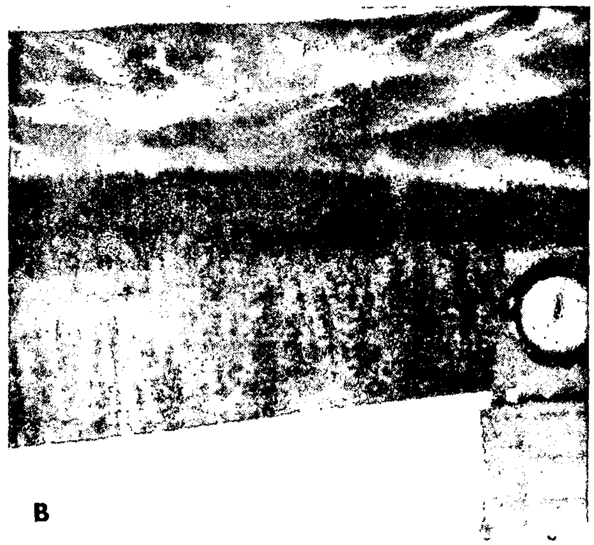

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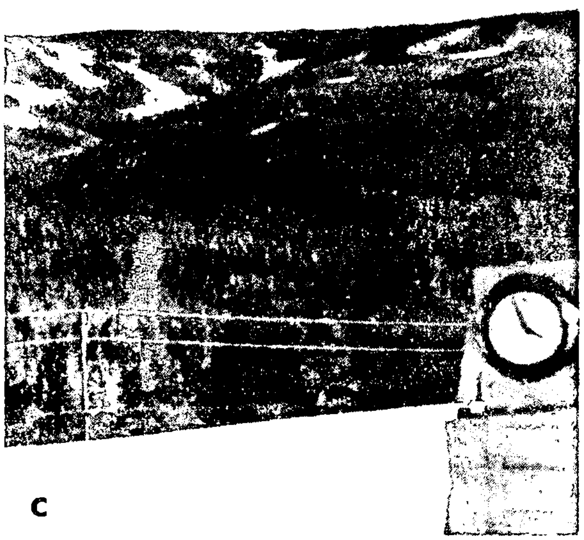

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Figure 12. Significance of wind-caused snow redistribution in the subalpine zone. (Leaf, 1975).

A This photograph was taken during moderate snowfall that continued throughout the day of February 4, 1970, at the Fraser Experimental Forest. The storm ceased during the night.

B The most exposed trees were already bare of snow by noon on February 5, 1970. Individual vortexes look like artillery bursts on the mountainsides. Vortexes were moving rapidly eastward (from right to left), and each one was visible for less than 60 seconds.

C By 4:00 p.m. on February 5, 1970, all snow was gone from exposed tree crowns. The white patches are snow in the clearcut blocks on the upper portion of the Fool Creek watershed.

where S,e, and P are as previously defined in equation [2];

I_s = interception storage;

k = a constant expressing the rate of interception storage; and

Po = the amount of snowfall accumulated at the time of most rapid storage (the point of inflection of the sigmoid curve).

However, in addition to interception processes, the aerodynamic characteristics of the watershed are modified through forest cover removal. The aerodynamic change in roughness modifies the patterns of snow accumulation, so that more snow accumulates in the cutover area (provided that openings are small) and less accumulates in the uncut forest. For optimum snow accumulation, openings should be protected from wind and should not exceed perhaps eight times the height of the surrounding forest. Larger openings apparently allow wind eddies to scour the snowpack near the center.

Conspicuous increases in snow accumulation near the center of small forest openings are largely offset by decreases in snowpack below the trees so that total snow storage on watersheds subjected to cutting is not changed. However, when openings are large, watershed snow storage may actually be decreased through large sublimation losses and transport of snow out of the basin. Figure 13 shows that for optimum snow accumulation, 5H is perhaps an absolute maximum. The lower curve, based on measurements in Wyoming by Tabler[1/] suggest high losses in large openings in high wind areas.

[1/]Personal communication with Dr. Ronald Tabler, Project Leader, Rocky Mountain Forest and Range Experiment Station, Laramie, Wyoming.

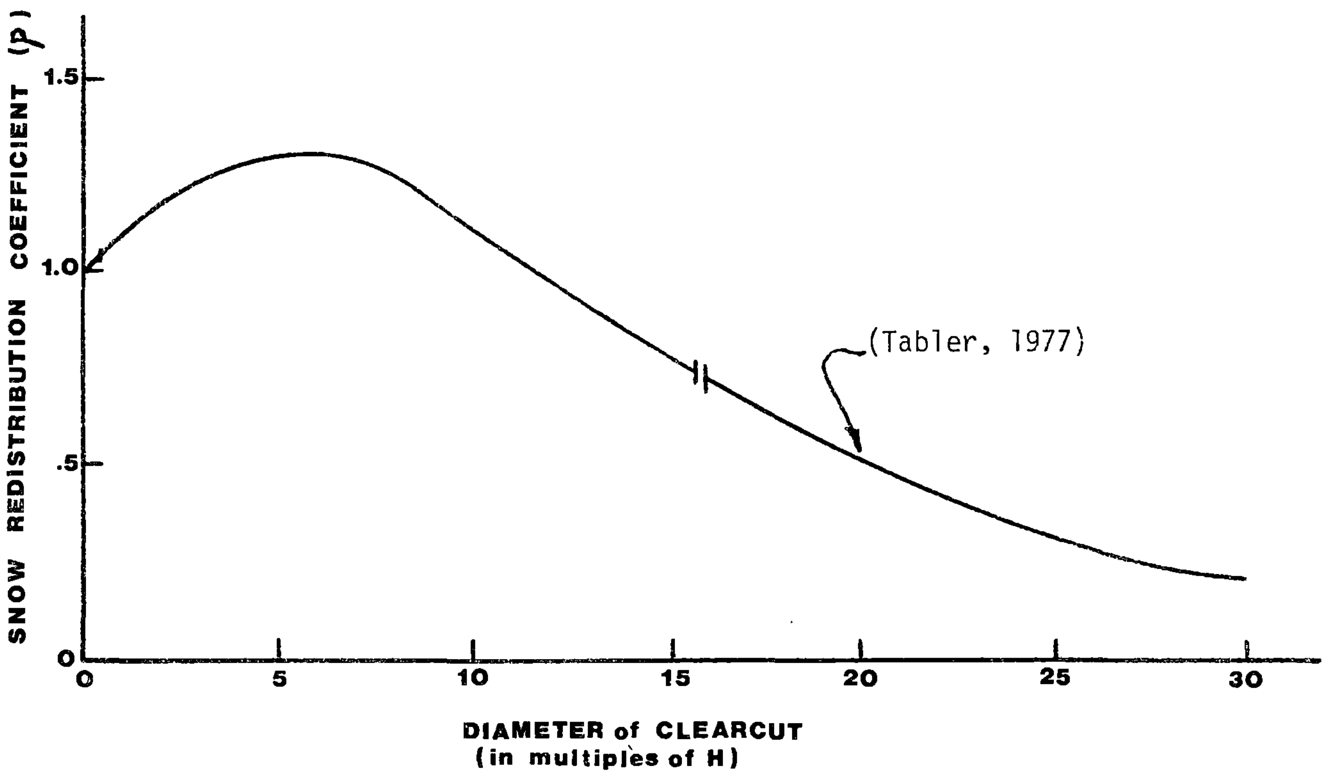

Figure 13.--Snow redistribution as a function of size of clearcut.

Again, objective methods for quantifying the effects of forest cover manipulation on snow redistribution are not yet available. Accordingly, quantification of these effects must be based on considerable judgment and experience in a particular area.

Snowmelt - Thermal Indices

In the United States, snowmelt processes have been the subject of study since the late 30's. Perhaps the most recent review of the more useful equations and techniques for estimating snowmelt is given by Anderson (1976). Chow (1964) also treats the subject of snowmelt in some detail.

Perhaps the simplest method of estimating snowmelt is the air temperature index method given by the general equation (U.S. Army, 1960):

1. For open sites,

$$M = 0.06\ (T_{mean} - T_2) \quad [13]$$

$$M = 0.04\ (T_{max} - T_3) \quad [14]$$

2. For forest sites,

$$M = 0.05\ (T_{mean} - T_4) \quad [15]$$

$$M = 0.04\ (T_{max} - T_5) \quad [16]$$

where M = inches of snowmelt per day,

T_{max} = the daily maximum temperature in °F;

T_{mean} = the mean daily temperature in °F; and

$T_2 .. T_5$ = temperature thresholds below which no snowmelt can occur.

Equations [13]-[16] provide reasonable estimates when the objective is merely to predict snowmelt. However, they are not adequate for evaluating the impacts on snowmelt of a wide range of treatments, because they do not adequately consider the complex energy exchanges that take place between the forest cover and snow environment.

Research has shown that solar radiation is primarily responsible for snowmelt, although there may be exceptions in those areas where large quantities of energy are involved in the sensible (convection/advection) and latent (evaporation/condensation) heat exchange processes. However, even in these areas, adequate determination of the sensible and latent heat exchange processes require more data and sophisticated analytical tools than are normally available to the forest hydrologist. Accordingly, the best approach is perhaps to: (1) estimate the energy balance from incoming solar radiation, and temperature and (b) modify the basic equations to account for sensible and latent heat exchange in those areas where these processes significantly affect snowmelt.

Energy Balance Equations for Snowmelt

Anderson (1976) has developed perhaps the most comprehensive snowmelt model to date. Although it is a research model and too complex for practical application, Anderson has stated ...

> "in the long term such research models should result in improved operational models. Improvements to current operational snow cover simulation models will likely be as a result of a more thorough understanding of the basic energy transfer processes and their interactions. Only with such an understanding can the effect of various assumptions, approximations, and simplifications which are a part of operational snow cover models be evaluated."

The reader is referred to the above publication for a complete discussion of the basic energy transfer processes and their interactions.

The snowmelt model summarized below is not a true energy-balance model since it computes snowmelt by one set of equations and the change in the heat deficit of the snow cover by a separate equation.

Snowpack Condition

In those areas where the snowpack stays below 0°C for much of the winter season, its temperature can be estimated from the one-dimensional Fourier heat-conduction equation (Leaf and Brink, 1973a).

Snowmelt - Energy Balance

When a snowpack becomes isothermal, and its free-waterholding capacity has been satisfied, the following general equation can be used to compute snowmelt:

$$M = f\left[S_w(1.0 - R_s)T + C_d(\sigma T_a{}^4 - \sigma T_s{}^4) + (1.0 - C_d)(\alpha\sigma T_a{}^4 - \sigma T_s{}^4)\right] \quad [17]$$

where M = Daily snowmelt in calories per cm^2

S_w = Incoming solar radiation in ly per day;

R = Reflectivity of snowpack, expressed as a decimal;

T = Shortwave radiation transmissivity coefficient, as expressed as a decimal;

C_d = Forest canopy density, expressed as a decimal;

σ = Stefan-Boltzmann Constant;

T_a = Air temperature in °K;

T_s = Snow surface temperature in °K;

α = Coefficient for computing sky radiation, expressed as a decimal. On clear days, α = 0.76, whereas on cloudy days, α = 1.00.

As seen in equation [17], snowmelt is assumed to be the result of:

1. Incoming shortwave radiation adjusted for the albedo of the snowpack,
2. The longwave balance between the snowpack and sky, and
3. The longwave balance between the forest cover and snowpack.

Longwave radiation is computed by the Stefan-Boltzmann function as follows:

$$L_p = \sigma T^4 \qquad [18]$$

where L_p = potential longwave radiation at a given temperature

σ = Stefan-Boltzmann constant for a 24-hour period: 1.17×10^{-7} (langleys)/(day)/(°K)$^{-4}$, and

T = temperature in °K.

The shortwave radiation component in the radiation balance is computed as a simple function of the transmissivity coefficient and the forest cover density. Solar radiation is adjusted for slope and aspect, according to tables published by Frank and Lee (1966). The downward longwave component is computed by using the average air temperature in the Stefan-Boltzmann function according to the equations:

FROM SKY TO SNOW:

$$L_s = \alpha(1 - C_D)(1.17 \times 10^{-7})(T_A{}^4) \qquad [19]$$

where C_D = forest cover density expressed as a decimal.

T_A = ambient air temperature in °K, and

α = a factor (1 or 0.75) which accounts for clear or cloudy skies.

FROM FOREST COVER TO SNOW:

$$L_F = 1.17 \times 10^{-7} C_D T_F^4 \qquad [20]$$

where T_F = radiation temperature of foliage in °K.

The upward component (back radiation) is computed by using either the average daily air temperature ("winter" conditions) or the minimum air temperature ("spring" conditions) for the radiation temperature of the snowpack. In the case of the back radiation, however, the temperature used must be less than or equal to 0°C. The equations used are:

FROM SNOWPACK TO FOREST:

$$L_{SF} = 1.17 \times 10^{-7} C_D T_S^4 \qquad [21]$$

where T_S = radiation temperature of the snowpack in °K.

FROM SNOWPACK TO SKY:

$$L_{SS} = (1 - C_D)(1.17 \times 10^{-7})(T_S^4)$$

Once the upward and downward components have been calculated, they are combined to get a net longwave balance as follows: if the skies are clear (no precipitation), only 75 percent of the downward longwave radiation from the snowpack (U.S. Army, 1960). The radiation balance under the forest canopy is computed by equations [20] and [21]. During "winter" conditions, $T_F = T_S$ and $L_F = L_{SF}$. If there was precipitation, a check is made to see if it was snow. When there is snow, the longwave balance is assumed to be zero. Otherwise, under cloudy skies, the downward component and the back radiation are merely combined algebraically.

The effects of a rainfall event on the snowpack is given by the following equation:

$$L_W = (C_R)(\Delta T)(P_R) \qquad [22]$$

where L_W = calorie gain due to rainfall

C_R = specific heat of water: 1 cal/gm/°C,

ΔT = difference between temperature (°C) at which rain falls and 0°C, and

P_R = amount of rainfall in centimeters.

If the pack is cold, the caloric input from the rain is used to satisfy all or part of the calorie deficit. If the input more than satisfies the deficit, the remainder is contributed as free water and the caloric input from that remaining is allowed to generate other melt. If the pack was already isothermal, the entire amount of rain is added to the pack as free water, and the calories contribute to the melt rate.

For snowfall, the effects on the pack are given by:

$$L_I = (C_S)(\Delta T)(P_S) \qquad [23]$$

where L_I = calorie gain or loss due to snowfall,

C_S = specific heat of ice: 0.5 cal/gm/°C,

ΔT = difference between temperature (°C) at which snow falls and 0°C, and

P_S = water equivalent of snowfall in centimeters.

If the snow falls within the "warm" range of say 30° to 35°F, there is no caloric loss. However, snow falling at lower temperatures increases the calorie deficit.

Forest Cover Density

Equations [17] - [24] for estimating snowmelt are expressed in terms of a parameter: FOREST COVER DENSITY.

In this discussion, forest cover density is not defined as "canopy" or "crown" closure, but rather as a tree parameter which integrates the net effects of the overstory on the transmission of solar radiation to the forest floor. Forest cover density varies according to crown closure, the vertical foliage distribution, species, season, and stocking. Empirical relationships between various timber stand variables and percent radiation beneath the forest canopy (transmissivity coefficient) are available in the literature for the major tree species (see Miller, 1959; Muller, 1971; Solomon et al., 1976; Vezina, 1965; Shomaker, 1968; Lull and Reigner, 1967; Gay et al., 1971; Federer, 1971; Brown, 1972).

In the Rocky Mountain/Inland Intermountain subalpine zone, the transmissivity coefficient can be approximated by the equation:

$$T_M = Z(Cdmx)^{\psi} \qquad [24]$$

where $T_M = Z(C_{dmx})^{\psi}$

T_M = the transmissivity of the forest canopy expressed as a decimal fraction of the amount of solar radiation available above the forest canopy;

C_{dmx} = the natural old-growth forest cover density expressed as a decimal, and

Z and ψ = parameters characteristic of the forest stand.

For example, combinations of C_{dmx} and T that were found acceptable for lodgepole pine, aspen, and spruce-fir in central Colorado are summarized below:

Forest type	C_{dmx}	T
lodgepole pine	0.25-0.45	0.30-0.30
spruce-fir	0.50-0.65	0.30-0.25
aspen		
foliated	0.35	0.35
defoliated	0.20	0.50

The resulting equation derived from these data is given as:

$$T = 0.19\, C_{dmx}^{-0.6}$$

As trees reoccupy cutover areas, forest cover density (C_d) increases with time until it reaches a maximum value. Research has shown that the rate at which forest cover density reaches this plateau depends on environmental conditions, stocking levels, and species. In subalpine coniferous forests in the Rocky Mountains for example, it can vary from 30 to more than 80 years.

In warm, humid climates, recovery can occur in just a few years after initial cutting.

Thus, C_d can vary as a function of time according to the following equation:

$$C_d = \frac{C_{dmx}}{\Phi^2} (t - t_{c_2})^2 \qquad t_{c_2} \leq t \leq \Phi \qquad [25]$$

where C_d = intermediate forest cover density expressed as a decimal.

Φ = the time in years from t_{c_2} at which maximum forest cover density is reached. This parameter was assumed to vary according to vegetation type as follows:

Forest species	Φ
lodgepole pine	40 years
spruce-fir	80 years
aspen	20 years and

t_{c_2} = critical time at which regeneration is sufficient to reestablish the stand when $t < t_{c_2}$, $C_d = 0$.

Evapotranspiration

Morton (1971) points out that "the relationship between potential evaporation and regional (actual) evaporation includes the effects of hydrologic climatologic feedback." The feedback includes moisture supply and the thermal and moisture characteristics of the overlying air, which are influenced by the actual evapotranspiration. This interaction in turn, has a significant influence on the energy available for evapotranspiration.

These interactions have also been taken into account by Bouchet (1963), who argued that changes in regional and potential evaporation due to changes in regional moisture supply are complementary. If the potential evapotranspiration (ET) is computed from regional climatological observations and utilized in this concept, the regional (actual) evapotranspiration, which is a product of complex climatic, soil moisture, and vegetative processes may be estimated.

One of the several empirical methods available for computing potential evapotranspiration is the one developed by Hamon (1961):

$$E_h = CD^2 p_t \qquad [26]$$

for computing average potential evapotranspiration, E_h (inches/day), for each month of the year

where D = possible sunshine in units of 12 hours,

p_t = the saturated water vapor density (absolute humidity) at the daily mean temperature in grams per cubic meter, and

C = a coefficient (0.0055 according to Hamon).

Hamon's equation requires only latitude, converted to day length (adjusted for slope and aspect), and mean temperature, converted to saturation vapor density, for computing monthly E_h.

Equation [26] predicts the "average" evapotranspiration. In many forested areas, this average is less than half the amount that could occur under conditions of unlimited energy supply, assumed herein as potential solar radiation. Accordingly, the coefficient C in equation [26] must be adjusted upward to obtain an expression for potential evapotranspiration under maximum solar input:

$$E_m = C' \ D^2 p_t \qquad [27]$$

where C' is the adjusted coefficient. The daily potential evapotranspiration for each of 12 months as derived by equation [27] is supplied as a set of parameters for each hydrologic subunit.

To adjust maximum daily evapotranspiration for available energy, the values determined by equation [27] can be computed according to the expression

$$E_s = \frac{SW}{P} E_m \qquad [28]$$

where E_s = evapotranspiration adjusted for available energy in inches/day,

SW = the observed daily shortwave radiation in langleys,

P = potential shortwave radiation for the day as computed by Frank and Lee (1966).

The adjusted evapotranspiration as derived above is then redefined, depending on the source, as selected by the following sequence:

1. If snow or rainfall is intercepted on the forest canopy, it can be assumed that evaporation occurs exclusively from that source.
2. If the canopy is free of intercepted snow or rainfall, the next step is to determine if losses result from evapotranspiration (see equations for computing evapotranspiration as a function of available energy and soil water) or evaporation from the ground surface.

If evaporation is from the snow or ground surface (Vg), it can be computed according to the expression:

$$V_g = (1 - C_d)E_s \qquad [29]$$

when $C_d = 0$ (a forest opening),

$$V_g = E_s.$$

Vaporization of intercepted precipitation can be estimated by the equation:

$$V_c = \frac{1}{C_d} E_s \qquad [30]$$

where V_c = intercepted precipitation evaporation in inches,

$C_d > 0$.

If equation [30] yields a value which is less than the water equivalent of the intercepted precipitation, that water equivalent is merely reduced to satisfy the evaporation requirement, V_c. However, if equation [30] indicates a greater value than the intercepted water equivalent, V_c is reduced to the point where the requirement is satisfied by the water equivalent of the intercepted precipitation, which is completely vaporized from the canopy.

Once the evapotranspiration requirements have been satisfied, any remaining input, either from snowmelt or rainfall, is used to satisfy the soil mantle recharge requirements. When field capacity is reached, the excess input is considered to be water available for streamflow (generated runoff).

Effects of Forest Cover Removal

Thus far, it is seen that man-made changes in the forest cover can produce changes in runoff by affecting the energy balance, pattern of snow and rainfall accumulation, and consumptive use. Hydrologic changes resulting from timber harvest will persist for only a short time or for many years, depending on the hydrologic regime. The Fool Creek study in central Colorado showed that water yield increases did not decrease significantly more than 16 years after treatment. Several hydrologic processes affected by forest cutting vary with time.

Evapotranspiration is one of the most significant processes modified by logging. A reasonable assumption is that water use by old-growth forest during the growing season proceeds at rates limited only by available energy until the soil water is depleted to perhaps 50 percent of the maximum "available" for transpiration (field capacity index). Thereafter, transpiration decreases in proportion to the amount of soil water below one-half of the field capacity index. In open or cutover areas, the absence of dense vegetation and a shallow rooting depth enables evapotranspiration to proceed at maximum rates only when the soil mantle is completely recharged. Thereafter, evapotranspiration decreases toward zero at perhaps three-fourths of the field capacity index. Assumed relationships are shown graphically in Figure 14. As forest vegetation reoccupies cutover areas, and consumptive use is increased, the relationship in Figure 14 changes until ultimately, as the forest cover is reestablished, it approaches that of the old-growth forest curve. It is this phenomenon which is primarily responsible for diminishing water yield increase over time following timber harvest. The rate at which this transition takes place depends upon forest species, climate, and stand conditions.

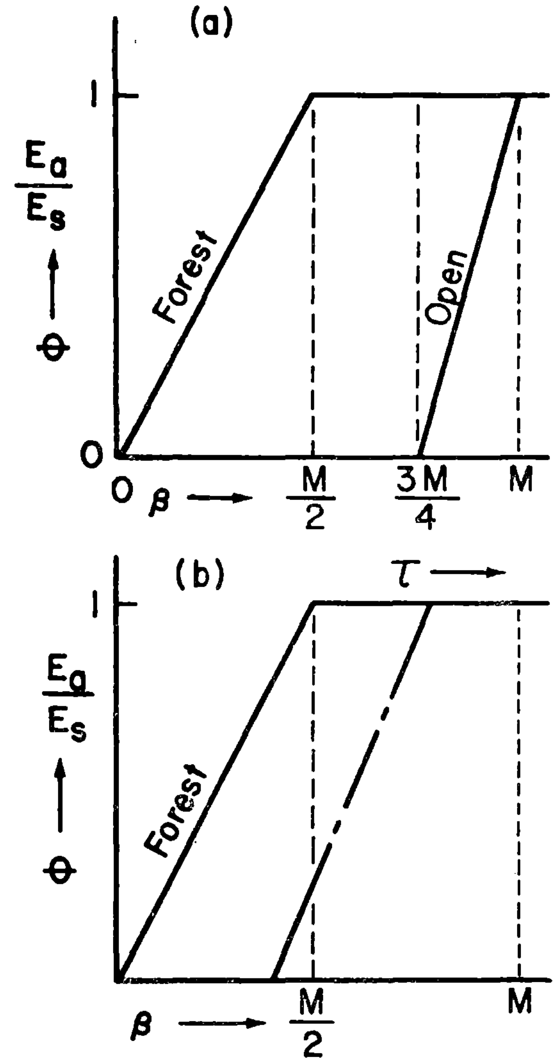

Figure 14.--Relationships showing evapotranspiration as function of available soil water for: (a) old-growth forest and open conditions, and (b) old-growth forest and some intermediate forest cover condition several years after timber harvesting. (Leaf and Brink, 1975).

A general expression for the relations shown in Figure 14 can be written as follows:

$$\theta = \Delta\left[\beta - \left(\tau - \frac{1}{\Delta}\right)\right] = \Delta(\beta - \tau) + 1 \qquad \begin{array}{l} \beta \geq \tau,\ \theta = 1 \\ \tau - \frac{1}{\Delta} < \beta < \tau \\ \beta < \tau - \frac{1}{\Delta},\ \theta = 0 \end{array} \quad [31]$$

where θ = the ratio, $\frac{E_a}{E_s}$. (E_a) is the actual evapotranspiration rate and (E_s) is computed in this model by a modified version of the Hamon equation (Leaf and Brink, 1973b).

β = the available soil water at any time. (β) can vary between 0 and M, where M is the "field capacity index,"

τ = the critical point at which available soil water begins to limit evapotranspiration. (τ) can vary between M/2 and M, and

Δ = the slope of the relationship between E_a/E_s = 0 and 1.

In addition to complex factors such as ecological habitat and stand condition, the rate at which a given forest reestablishes itself varies according to species. Discussions and background literature for the major forest types of the subalpine zone presented in subsequent discussions in these guidelines. Some tree species, as for example, spruce-fir forests are very difficult to regenerate, and therefore, require the longest period of time for regrowth, whereas other species, due to environment, seed production, and growth habits, do not require as much time to reestablish themselves. Finally, since some hardwoods regenerate from root sprouts, a new stand promptly occupies the site, and on many sites growth can exceed that of associated conifers for decades.

The type of information discussed above can be used to develop the time-trend relationships discussed below.

The reader should note that the procedure used in deriving the assumed time-trend equations is to: (a) establish plateaus, and maximum and minimum values for each hydrologic parameter; (b) establish critical values at which a transition takes place (that is, "when things begin to happen"); and (c) assume a functional relationship for each process which determines all intermediate values with respect to time.

It is emphasized that the time-trend relationships may not be inherently correct; however, they are plausible in light of our present understanding of long-term hydrologic phenomena. The validity of the equations should be determined by additional research.

Soil Water.--The critical point at which available soil water begins to limit evapotranspiration (τ), can be assumed to vary with time and species as shown in Figure 15 for the three primary species in the Rocky Mountain Subalpine Zone. These relationships can be:

$$\tau = Me^{-k(t - t_{c_1})} \qquad \begin{array}{l} \tau = M,\ t < t_{c_1} \\ \tau = M/2,\ t > t_r \end{array} \qquad [32]$$

where k = an index of the rate of decline of τ,

t_{c_1} = the time at which available soil water begins to limit evapotranspiration in years, and

t_r = the time at which the hydrologic effect of timber harvesting becomes insignificant.

The parameters, k and t_{c_1}, vary according to forest species as seen in Figure 15. When $t \leq t_{c_1}$, no adjustments are made in the soil water correction, since watershed experiments indicate that a correction is not warranted for a number of years after timber harvest. For example, assumed values of t_{c_1}, t_r, and k for the three primary species in the Rocky Mountain Subalpine Zone are summarized below:

Forest species	t_{c_1}	t_r	k
aspen	7 years	60 years	0.01
lodgepole pine	15 years	80 years	.01
spruce-fir	30 years	100 years	.01

The assumed relationship between Λ and τ is shown in Figure 16, and is given by

$$\Lambda = \frac{4\tau}{M^2} \qquad [33]$$

Substituting equation [32] and [33] into equation [31] yields

$$\theta = 4e^{-k(t - t_{c_1})}\left[\beta/M - e^{-k(t - t_{c_1})}\right] + 1 \qquad [34]$$

which is a general equation for θ as a function of forest cover type, field capacity index, and time.

Radiation Balance and Evapotranspiration According to Forest Cover Density

Baumgartner (1967) and Tajchman (1971) have reported that evapotranspiration from coniferous forests is greater than from open land, although Tajchman reported small differences between forest and open land than did Baumgartner. Both Baumgartner and Tajchman discussed the

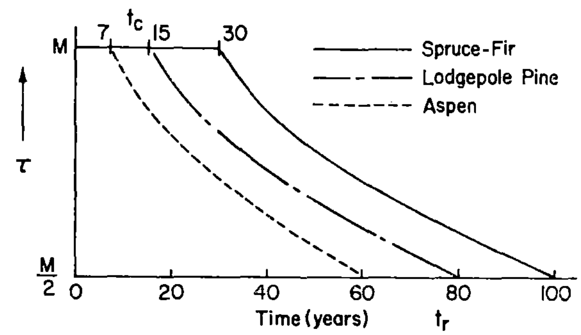

Figure 15.--Assumed variation of τ with time and vegetation type for three primary tree species in the Rocky Mountain subalpine zone. (Leaf and Brink, 1975)

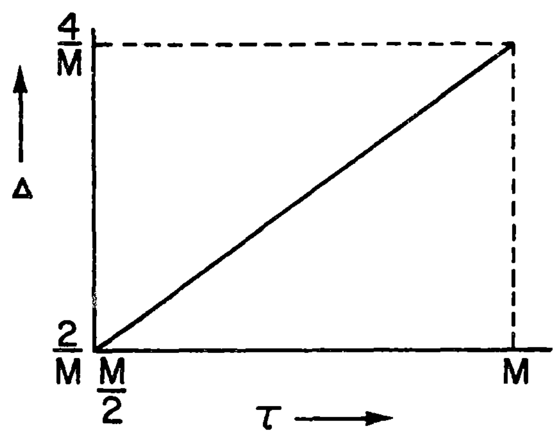

Figure 16.--Assumed variation of Δ as a function of τ. (Leaf and Brink, 1975)

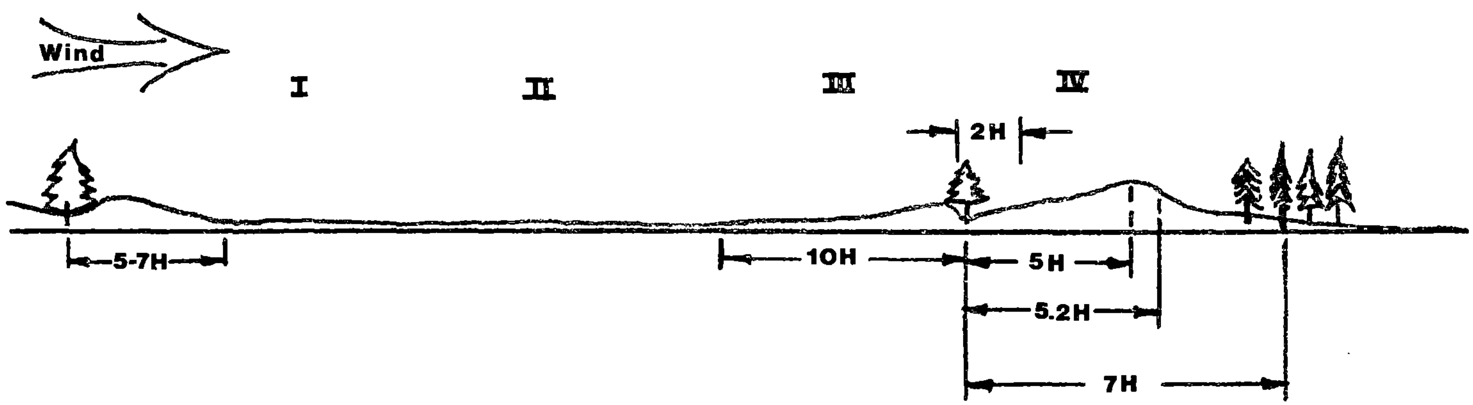

Figure 17-1.--General pattern of snow accumulation in large clearcut blocks. (Tabler, 1977).

differences in evapotranspiration from various cover types in terms of the differing energy balances. In presenting an analysis of the radiation balance and associated vapor loss, Baumgartner (1967) pointed out that "the only pertinent variations with regard to the latent heat flux are those associated with reflectivity . . ." Accordingly, a relationship can be derived between reflectivity and forest cover density to index the reduction of evapotranspiration as forest cover is removed as follows:

$$R_f = R_{fo} \exp\left[\frac{\omega C_{dmx}(t - t_{c_2})^2}{\Phi^2}\right] \qquad [35]$$

where R_f = the reflectivity of the forest stand,

R_{fo} = the reflectivity of a forest opening (assumed herein as 0.5). When $t < t_{c_2}$, $R_f = 0.5$, and

$\omega = 1.609\ C_{dmx}^{-1}$.

Computations for evapotranspiration subsequent to silvicultural activities must incorporate the effects of regeneration of the forest stand as discussed above. However, as explained below additional modifications of the adjustment factor for available soil water (equation [34]) must also be made. The potential evapotranspiration, E_s, given by equation [28] must be adjusted for both the available soil water and forest canopy reflectivity (equation [35]) to produce the actual evapotranspiration (E_a). It should be noted that equation [35] is constant over a water year and is recomputed after each growing season.

Interception

Allowance must be made for snow and rainfall interception to take place as the forest cover reestablishes itself after harvest cutting. This is accomplished on the cutover areas by weighting the effects of both evaporation from areas not occupied by trees and evaporation from intercepted precipitation. Evaporation from the ground or snow surface and from interception is computed by equations [29] and [30].

It can be assumed that when $C_d \geq \frac{C_{dmx}}{2}$, and precipitation rests on the canopy, evaporation is computed by equation [30], whereas during conditions when the canopy is free of intercepted precipitation, evaporation takes place from the snow or ground surface according to equation [29]. However, when $0 < C_d < \frac{C_{dmx}}{2}$, both equations [29] and [30] can be used as follows:

$$V_t = E_s \left[\frac{2}{C_{dmx}} + \left(1 - \frac{2C_d}{C_{dmx}} \right) \left(1 - C_d \right) \right] \qquad [36]$$

V_t = combined evaporation from snow surface and intercepted snow in cutover areas.

Snow Redistribution

The hydrologic significance of snow redistribution which occurs in many parts of the United States has already been discussed.

Redistribution of snow as a result of forest cutting is a significant factor influencing runoff. For example, in the lodgepole pine type in Colorado, this phenomenon is not greatly diminished more than 30 years after timber harvest in spite of regrowth of trees and associated increase in forest cover density (Figure 17). It is believed that changes in natural snow accumulation patterns produced by timber harvest will persist until the new crop of trees approaches the height of the remaining virgin forest.

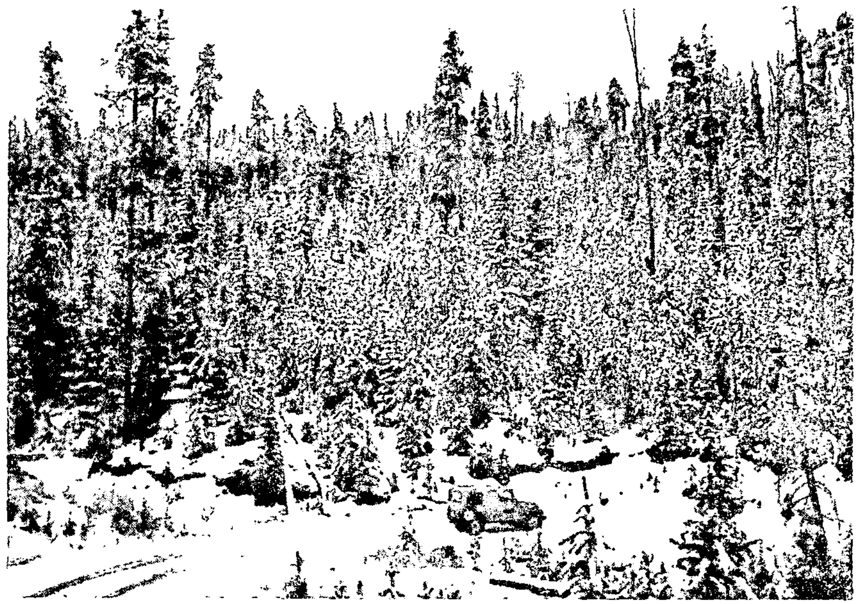

Figure 17.-New growth does not affect total snow storage in this lodgepole pine area of the Fraser Experimental Forest. This 8-acre plot, cut 28 years ago to remove all but 2,000 fbm of trees larger than 9.5 inches d.b.h., still functions as an opening with wind controlled by surrounding old-growth forest.
(Leaf, 1975)

Moreover, optimum redistribution of snow results when old-growth subalpine forests are (a) harvested in small patches less than 8 tree-heights in diameter; (b) protected from wind; and (c) interspersed so that they are 5 to 8 tree-heights apart. More snow is deposited in the openings, and less snow accumulates in the uncut forest so that total snow on head-water basins is not significantly increased. The following relationships can be developed for evaluating snow redistribution effects with time:

$$\rho = \rho_{mx}\left[\exp -k_1(t - t_{c_3})\right] \qquad \begin{array}{l} t \le t_{c_3},\ \rho = \rho_{mx} \\ t \ge t_{r_1},\ \rho = 1 \end{array} \qquad [37]$$

where ρ = snow redistribution factor in the cutover area which varies according to the silvicultural system used. For example, when 40 percent of the area is occupied by small openings 5 tree-heights in diameter, the winter snowpack is increased by 30 percent in the open and decreased 20 percent in uncut forest.

ρ_{mx} = the redistribution factor immediately after timber harvesting,

k_1 = an index of the rate of decline of ρ,

t_{c_3} = the time at which forest regrowth begins to reduce snow redistribution in years, and

t_{r_1} = the time at which forest regrowth causes snow redistribution to become insignificant.

The parameters, k, t_{r_1}, and t_{c_3} vary according to tree type. When $t \le t_{c_3}$, no adjustments need be made in the redistribution, since field studies at least in the Rocky Mountain Region indicate that a correction is not warranted for several years after harvest cutting.

Tabler has proposed equations for quantifying seasonal snow accumulation in each of the four zones. These equations are summarized in Table 2-A.

TABLE 2-A

SUMMARY OF EQUATIONS FOR QUANTIFYING SNOW ACCUMULATION IN LARGE CLEARCUTS (D > 15 H)

Zone	Parameter	Equation
I	Drift length	$L_I = 5\ H$
	Max. Snow Depth	$D_{mxI} = 3.33\ P$
	Precipitation Retained	$\rho_I = (2/3)\ P$
	Precipitation Relocated	$\theta_I = P/3$
	Snowpack Density	$\gamma_{sI} = 35\%$
II	Effective Length	$L_{II} = D - 15H$
	Max. Snow Depth	$D_{mxII} = \delta$
	Precipitation Retained	$\rho_{II} = 0.35\delta + \omega P$
	Precipitation Relocated	$\theta_{II} = 0.8P - 0.35\delta$
	Snowpack Density	$\gamma_{sII} = 35\%$
III	Drift Length	$L_{III} = 10H$
	Max. Snow Depth	$D_{mxIII} = \frac{1}{3}\left[4Q/5H + (2/3)P\right]$
	Precipitation Retained	$\rho_{III} = 0.2\delta + 0.0533\ Q/H + 0.133P$
	Precipitation Relocated	$\theta_{III} = P - 0.2\ \ + 0.0533\ Q/H + 0.133\ P$
	Snowpack Density	$\gamma_{sIII} = 40\%$
IV	Total Drift Length	$L_{IV} = 7H$
	Location of Max. Depth	$\ell = 5H$
	Deflation (Fig.17-1)	$d = 2H$
	Max. Snow Depth	$D_{mxIV} = 4Q/5H + (2/3)P$
	Snowpack Density	$\gamma_{sIV} = 50\%$

The terms in Table 2-A are defined as follows:

H = tree height in feet

D = clearcut diameter in feet

P = precipitation water equivalent in feet

ω = a coefficient which indexes the amount of over winter snowpack ablation (perhaps 0.2)

δ = roughness (splash, regeneration, height, etc. in feet

Q = total snow transport off the clearcut area (D) in ft^3/ft

The total water equivalent transport off the clearcut block in ft^3/ft can be computed by the equation:

$$Q = [5000/(1 + 250\ a/H)]\ \{0.87P - 0.2\delta + (0.13P - 0.15\delta)a + (0.35\delta - 2/3P)b - Pc/3\} \qquad [37a]$$

where:

$$a = 0.14^{\frac{10H}{10,000}}$$

$$b = 0.14^{\frac{D-5H}{10,000}}$$

$$c = 0.14^{\frac{D}{10,000}}$$

Evaporation losses are computed from the equation:

$$Q_{loss} = PD - 1.53Q - 4.67PH - 0.35\delta D + 3.25\delta H \qquad [37b]$$

The terms in this equation are defined above.

Solution of the equations proposed by Tabler enable one to determine evaporation losses associated with large clearcuts, which can be quite significant. For example a 3,000 ft. clearcut with δ = 2' can result in 27 percent less snow accumulation over the winter season. A case study by Tabler[1], in which an 1800 foot block was clearcut, and the slash subsequently windrowed and burned, resulted in 36 percent less snow accumulation than in the uncut stand.

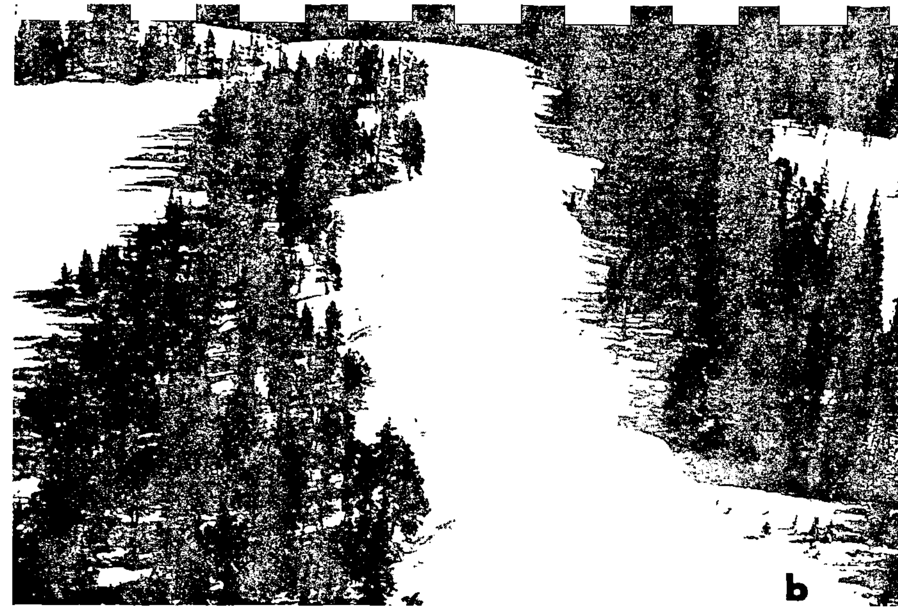

Figure 17-2.-- Cinnabar Park, Medicine Bow National Forest (NW¼ S36,T15N,R79W; elev. 9600 ft). Origin of park is unknown, but may have resulted from fire in young stand of LPP.

a). Wind left to right. Maximum width of park is about 2000 ft. Corridor or "snow glade" is kept clear of trees by snowdrift. 6/16/75 photo by A. L. Ward.

b). Wind left to right. 4/15/74 photo by A. L. Ward.

c). Drift in Cinnabar snow glade has maximum depth of about 35 ft. 5/2/75 photo by Tabler.

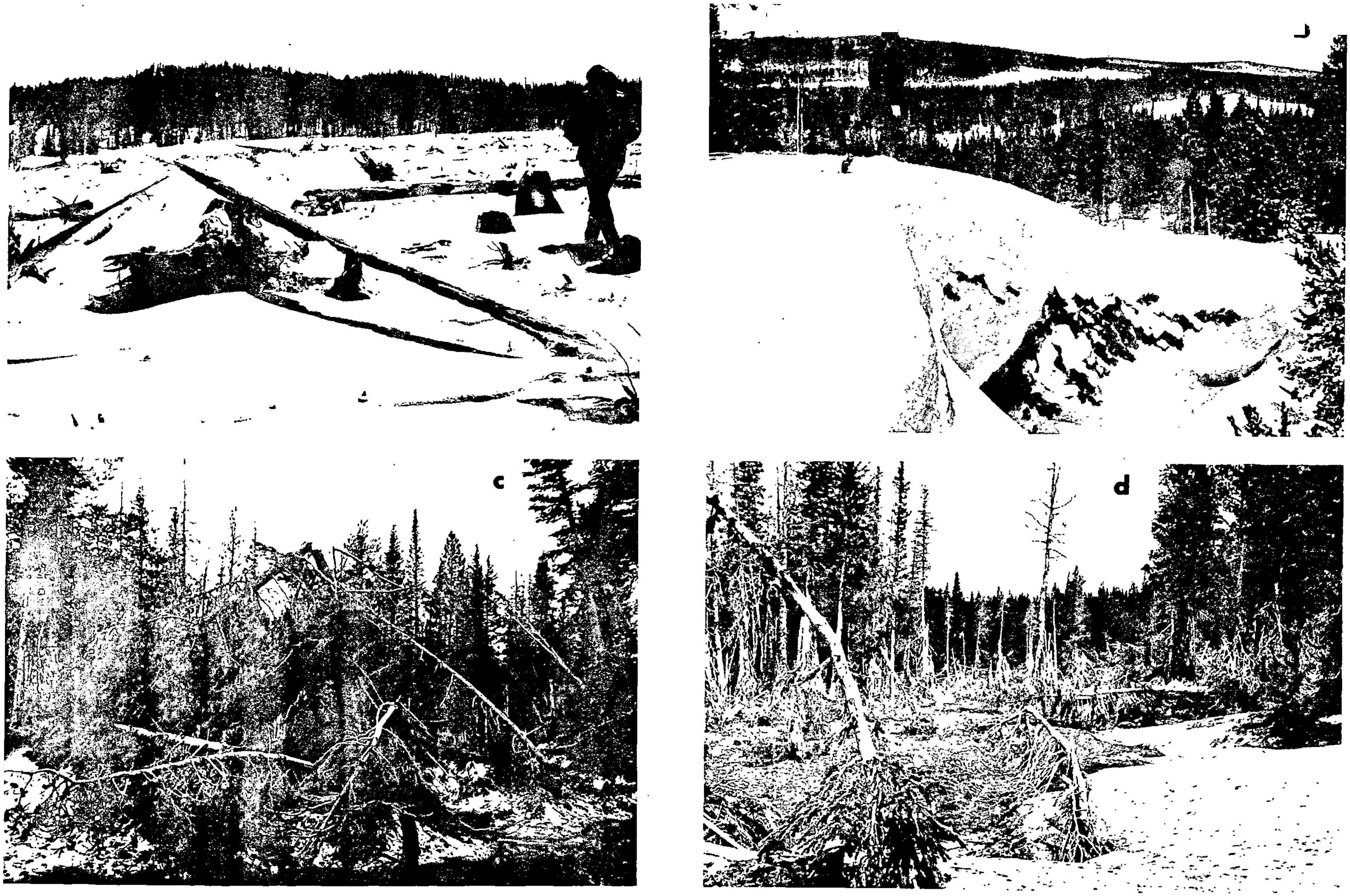

Figure 17-3.--Snow glades similar to that at Cinnabar Park are forming downwind of clearcut blocks on the Medicine Bow National Forest. This 45-acre block south of Rock Creek Park (SW¼ SE¼ S32, T17N,R78W) was cut in 1967, with slash windrowed and burned in 1968. Elevation = 10,000 ft. Width parallel to wind = 1800 ft.

a). Very little snow is retained on the clearcut--about 90% of the winter precip. is blown off by the wind. (5/1/75 photo by Tabler)

b). Snowdrift is 35 ft deep (5/1/75 photo by Tabler)

c). Damage to trees results in snow glade shown in d). (8/14/75)

More views are shown in Fig. 3.

Figure 17-4.--Residual timber on downwind side of clearcut shown in Fig. 2. Late-lying snowdrift keeps soil saturated throughout summer, making trees more vulnerable to windthrow.

a). Windfall was salvaged in 1974, in a strip 100 to 200 ft wide on downwind side of block (8/14/75 photo by Tabler).

b). Windfall between clearcut and glade accumulated since 1974 salvage (8/11/76, Tabler). This view looks directly into wind.

Figure 17-5.--Windfall on lee side of 1972/73 clearcut between North and Middle Forks of Rock Creek (E½ S12,T17N,R79W). Wind is channeled into "corner" by forest margin. Salvage is being considered as part of the proposed Sand Lake Sale. 8/11/76 photo by Tabler.

Figures 17-2 through 17-5 by Tabler graphically show the effects of large clearcuts in Wyoming. Undesirable impacts include not only reduced snow accumulation, but also damage to the residual forest from wind and excessive snow accumulation in Zone IV.

Individual-Tree Selection Cutting

Selection cutting also corresponds to a reduction of the forest cover density (C_d). The degree that C_d is reduced depends on characteristics of the stand and the volume of timber removed. In very mature stands, if C_d is reduced by 50 percent or less from C_{dmx}, forest canopy density probably does not increase subsequent to harvest cutting. However, if C_d is reduced more than 50 percent from C_{dmx}, it can be assumed that equation [25] approximates the redevelopment of forest cover density with time. Solving equation [25] for time yields:

$$t_\eta = \left(\frac{\Phi^2 C_d}{C_{dmx}}\right)^{1/2} + t_{c_2} \qquad [38]$$

If the degree to which thinning reduces C_{dmx} is given by η, then C_d is given by

$$C_d = C_{dmx}(1 - \eta)$$

Hence, equation [38] can be written as:

$$t_\eta = \Phi\left[(1 - \eta)\right]^{1/2} + t_{c_2} \qquad [39]$$

where t_η = the time required to reach the reduced forest cover density as if the stand were initially patch-cut, and

η = the degree that C_d is reduced from C_{dmx} (expressed as a decimal).

Hydrologic Simulation Models

As seen above, subalpine zone hydrologic processes are interactive and complex. Accordingly, hydrologists have resorted to dynamic process-oriented simulation models as a means of quantifying watershed disturbances.

Mathematical modeling, or the objective analysis of the information-feedback characteristics of hydrologic systems provide more convincing criteria by which to estimate system hydrology, since system structure, delay, and amplification are taken into consideration. The modeling approach involves six basic steps:

1. Construction of a dynamic mathematical model in which important interactions between system components are defined.
2. Programming and execution of the model over a period of time on a digital computer.
3. Comparison of model results against all pertinent available data. (The regional approach can be effectively used for model validation.)
4. Revision (tuning) of the model until it is acceptable as a representation of the actual system.
5. Alteration of certain model components in order to represent changes in the real system.
6. Repeat of step 3 to verify the "tuning" and/or model alteration.

The foregoing process is often called "simulation." Because the model represents the real dynamic system, changes in system behavior can be traced directly to their causes.

At each step in the above sequence, the prior steps often need to be revised. The whole procedure is not unlike the development of an aircraft or automobile, where repeated design changes and testing ultimately result in an operational prototype.

Simplicity is a primary consideration in modeling, and is generally achieved if the objectives of a model are precisely known. An effective model will not be overly complicated, will not have sophisticated data requirements, and will communicate easily with the practicing professional.

Perhaps the most important factor in model design and use has to do with proper selection of the range over which the model is valid. Again, suitable boundaries or limits for the model are related to concise objectives. If a model is applied in situations outside the range of conditions for which it was designed, then the results are often misleading.

Model application of particular interest in this investigation is the prediction of the impact produced by a change imposed on the system and the approximate extent of that impact. In order to rely on the model, one must be satisfied that it is an acceptable representation of the real system, and that model behavior corresponds to that of the real system.

While several so-called "objective" tests have been developed for model validation, no completely objective test exists, since all depend eventually on some underlying subjective premise (Forrester, 1969).

It should be borne in mind that the danger in any quantitative model-validation procedure is that it takes on an "aura of authenticity" which may lead the inexperienced modeler to forget the underlying subjective assumptions. Although some investigators may challenge the idea that at some point "objective" model validation procedures rest on a subjective foundation, primary confidence must depend on: (1) how acceptable or plausible the model is in describing natural processes, and (2) the reasonable assumption that "if all the necessary components are adequately described and properly interrelated, the model system cannot do other than behave as it should" (Forrester, 1969). Because much of the content of complex natural system models is derived from nonquantitative sources, the defense of such models ultimately must rest in careful subjective evaluation of their performance of experienced professionals who are familiar with these systems.

In practice, the utility of a mathematical model lies in its ability to precisely represent overall behavior of natural systems, and their response to changes in one or more system components. Accordingly, small changes in system response not otherwise detectable through statistical and regional analyses, can often be detected by careful simulation modeling.

Application and Use of Models

Jones and Leaf (1975) have reviewed several models developed for engineering hydrology. They vary widely in terms of complexity and scope, depending on application. All are based on a practical engineering approach which achieves a balance between: (1) theory, (2) available data, and (3) operational objectives and constraints. The successful application of each model depends to some extent on empirical derivations of several parameters and relationships, some of which are unique to the geographic

areas for which they were originally derived. Accordingly, adaptation of the models to other areas, in most cases, requires development of similar empirical relationships which reflect new conditions.

Recalling the six basic steps in the simulation approach mentioned previously, model adaptation is based primarily on trial-and-error solutions (tuning) to obtain acceptable responses based on historic data. This tuning procedure is repeated until satisfactory verification of observed streamflow is obtained.

Subalpine Water Balance Model

It is emphasized that a model should be well documented and applied to watersheds of the same character for which it was developed. One such model, the "Subalpine Water Balance Model," was chosen to simulate watersheds in the area of interest, since it was developed using the concepts summarized in equations [11] - [39] above, and calibrated for the high-elevation subalpine zone of the Central and Southern Rocky Mountains. This dynamic hydrologic model was developed by the U.S. Forest Service, and is specifically designed to simulate the hydrologic impacts of watershed management (Leaf and Brink, 1973b and Leaf and Brink, 1975). Figure 18 is a diagram of the basic model.

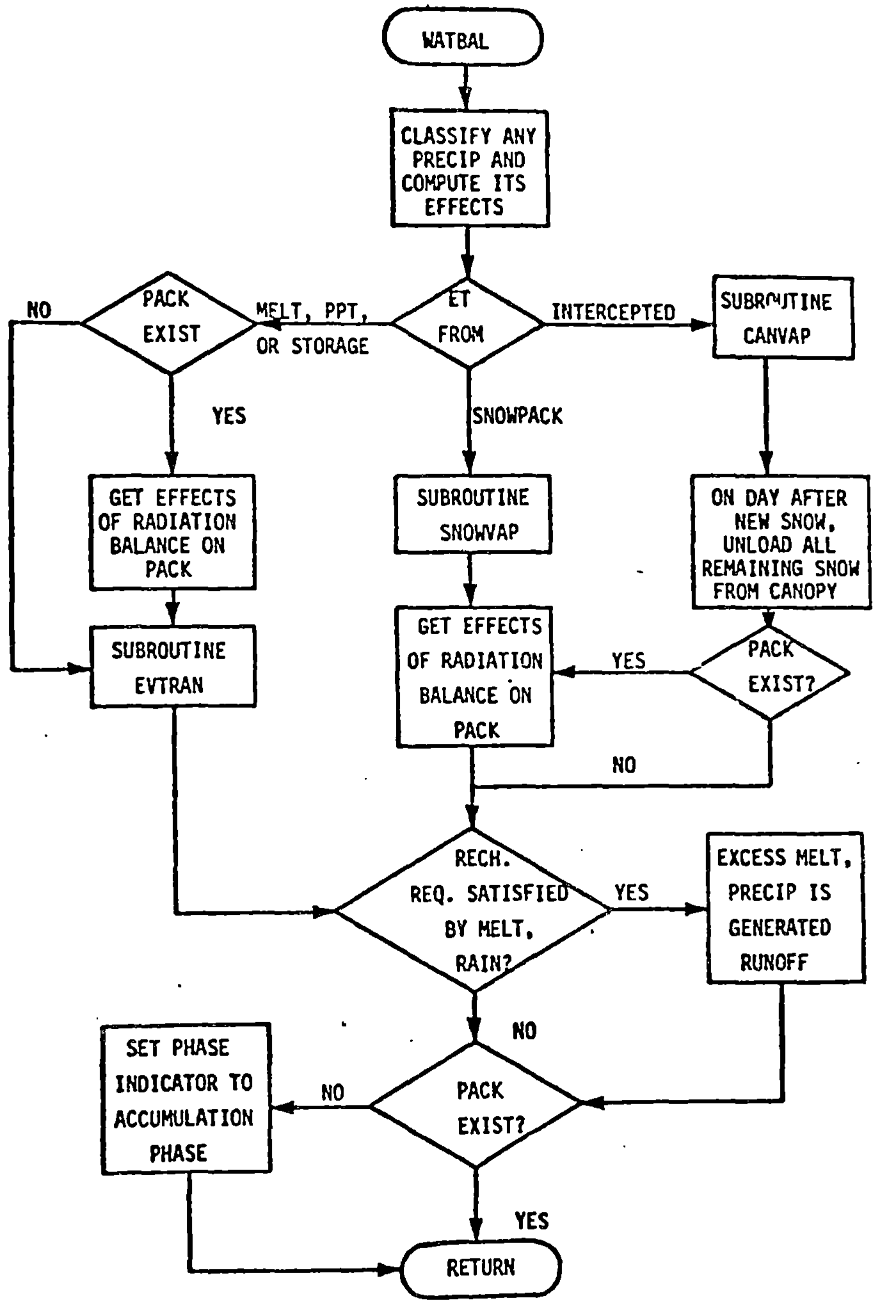

Figure 18.--General flow chart of Subalpine Water Balance Model (from Leaf and Brink 1973b).

Calibration of Subalpine Water Balance Model--

Diamond Creek

The Subalpine Water Balance Model has been used with good success on a number of representative watersheds throughout the Rocky Mountain Region. This section illustrates application of the model to Diamond Creek, a watershed in the Caribou National Forest, Idaho, which potentially could be impacted by high levels of phosphate mining activity (U.S. Forest Service, 1976). The location of this watershed is shown in Figure 19.

Watersheds Impacted by Mining Operation

Future mining operations could produce environmental impacts on at least four sub-watersheds. Accordingly, Diamond Creek was divided into four hydrologic subunits that vary according to slope, elevation, aspect, and forest cover (Table 3). The water balance was simulated on each subunit; area-weighted responses were computed and summed to obtain the overall response for the entire basin. Both time and spatial variations were taken into account.

Daily temperature extremes in each of the subunits were estimated by extrapolating published temperatures at Conda and Blackfoot Reservoir, cooperative stations operated by the National Weather Service. Because reliable long-term radiation data were not available in this area, shortwave radiation input to the model was generated from potential solar beam radiation at 42° N. Latitude and adjusted for the slope/aspect characteristics of each subunit. These values were further adjusted by empirically derived thermal factors to obtain an index of incident shortwave radiation each day. Peak snowpack accumulation on Diamond Creek was estimated from two snow courses observed by the U.S. Department of Agriculture Soil Conservation Service.

Figure 19.--Diamond Creek, Caribou National Forest, Idaho.

(map)

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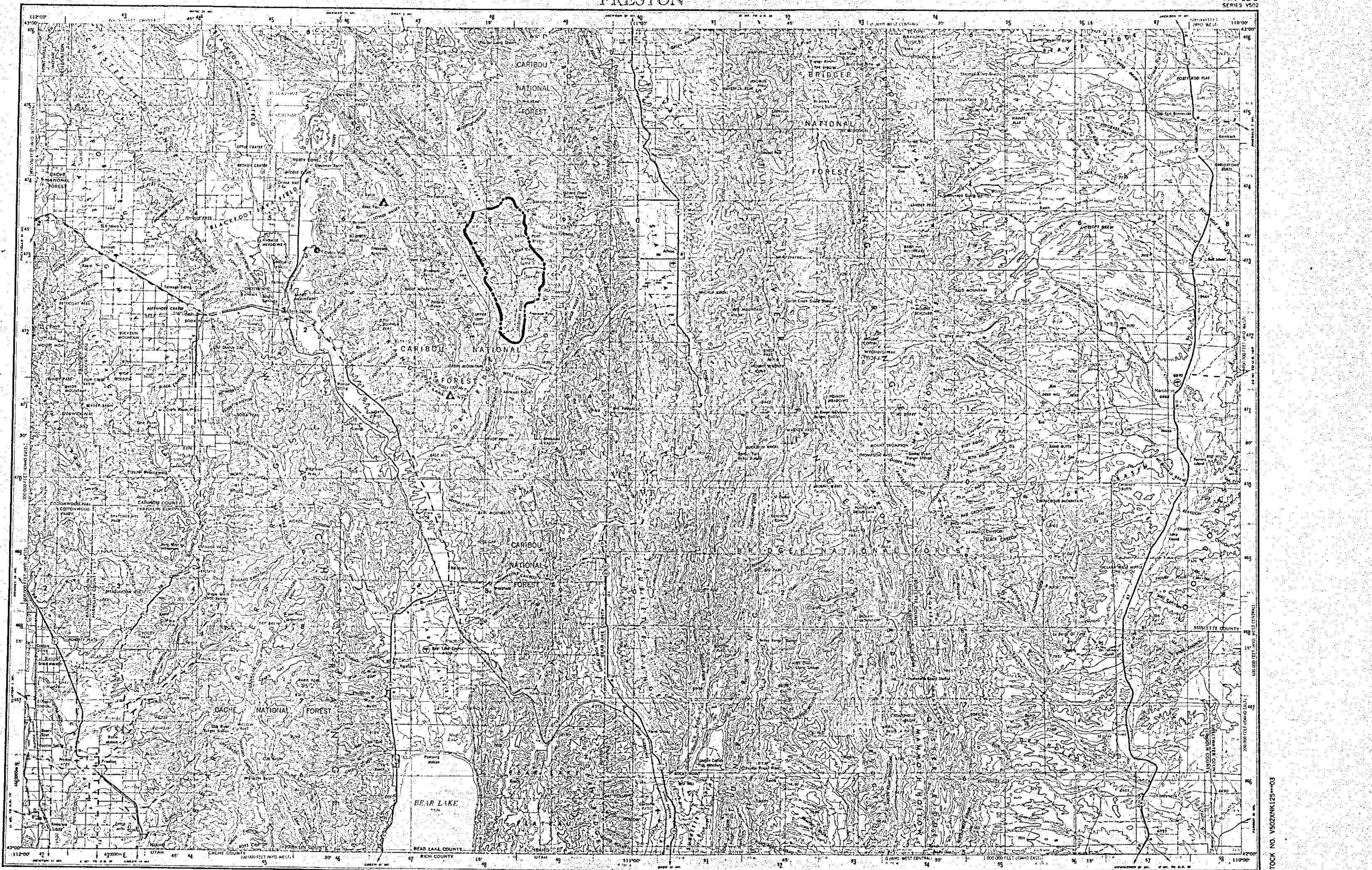

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Prepared by the Army Map Service (ASSX), Corps of Engineers, U.S. Army, Washington, D.C. Compiled in 1955 by photogrammetric methods and from USGS quadrangles, 1:24,000, 1:62,500 and 1:125,000, 1929-49. Planimetric detail revised by photo-planimetric methods. Horizontal and vertical control by USGS, USC&GS and USCE. Photography field annotated 1955. Limited revision by U.S. Geological Survey 1961.

100,000-foot grids based on Wyoming coordinate system, west and west central zones, and Idaho coordinate system, east zone

LEGEND

Figures in red denote approximate distances in miles between stars

POPULATED PLACES
Over 500,000 — LOS ANGELES
100,000 to 500,000 — OMAHA
25,000 to 100,000 — GALVESTON
5,000 to 25,000 — Laramie
1,000 to 5,000 — Grand Coulee
Less than 1,000 — Sun Valley

ROADS
Hard surface, heavy duty
More than two lanes wide
Two lanes wide; Federal route marker
Hard surface, medium duty
More than two lanes wide
Two lanes wide; State route marker
Improved light duty
Unimproved dirt
Trail

RAILROADS — Single track — Double or Multiple
Standard gauge
Narrow gauge

BOUNDARIES
International
State
County
Park or reservation

Landplane airport
Landing area
Seaplane airport
Seaplane anchorage
Woods-brushwood

Landmarks: School; Church; Other
Horizontal control point
Spot elevation in feet
Marsh or swamp
Intermittent or dry stream
Power line

Scale 1:250,000

5 0 5 10 15 20 Statute Miles
5 0 5 10 15 20 25 30 Kilometres
5 0 5 10 15 Nautical Miles

CONTOUR INTERVAL 200 FEET
WITH SUPPLEMENTARY CONTOURS AT 100 FOOT INTERVALS

TRANSVERSE MERCATOR PROJECTION

BLACK NUMBERED LINES INDICATE THE 10,000 METRE UNIVERSAL TRANSVERSE MERCATOR GRID, ZONE 12

THE MAGNETIC DECLINATION FOR THIS SHEET VARIES FROM 17°15' EASTERLY FOR THE CENTER OF THE WEST EDGE TO 16°30' EASTERLY FOR THE CENTER OF THE EAST EDGE. MEAN ANNUAL CHANGE IS 0°02' WESTERLY.

FOR SALE BY U.S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR RESTON, VIRGINIA 22092

LOCATION DIAGRAM FOR NK 12-5

NL 11-12	NL 12-10	NL 12-11	NL 12-12	NL 13-10
NK 11-3	NK 12-1	NK 12-2	NK 12-3	NK 13-1
NK 11-6	NK 12-4	NK 12-5	NK 12-6	NK 13-4
NK 11-9	NK 12-7	NK 12-8	NK 12-9	NK 13-7
NK 11-12	NK 12-10	NK 12-11	NK 12-12	NK 13-10

MONTANA, IDAHO, WYOMING, NEVADA, UTAH, COLORADO

SECTIONIZED TOWNSHIP

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

TOWNSHIP OR RANGE LINE
LAND GRANT BOUNDARY

GRID ZONE DESIGNATION: 12T

100,000 M. SQUARE IDENTIFICATION

VC WC
VB WB

IGNORE the SMALLER figures of any grid number; these are for finding the full coordinates. Use ONLY the LARGER figures of the grid number; example: 4660000

TO GIVE A STANDARD REFERENCE ON THIS SHEET TO NEAREST 1000 METRES

SAMPLE POINT: AFTON

1. Read letters identifying 100,000 metre square in which the point lies.
2. Locate first VERTICAL grid line to LEFT of point and read LARGE figure labeling the line either in the top or bottom margin, or on the line itself. Estimate tenths from grid line to point.
3. Locate first HORIZONTAL grid line BELOW point and read LARGE figure labeling the line either in the left or right margin, or on the line itself. Estimate tenths from grid line to point.

SAMPLE REFERENCE — VB8774
If reporting beyond 18° in any direction, prefix Grid Zone Designation, as: 12TVB8774

PRESTON, IDAHO; WYOMING
1955
Limited Revision 1961

Table 3.--Geographic characteristics

Diamond Creek, Caribou National Forest, Idaho

Subunit No.		Area (sq. mi.)	Slope (%)	Aspect	Mean Elev. (ft.)	Total Area (%)	Eff. Forest Cover Den. (%)
1		9.22	30	W	7600	20.4	
DWTW	-Φ					4.1	0
DWTW	-F					16.3	35
2		15.79	30	WSW	7400	35.0	
DO	-Φ					10.5	0
DO	-F					24.5	30
3		13.75	30	ENE	7600	30.4	
D76	-Φ					9.1	0
D76	-F					21.3	30
4		6.41	30	E	7800	14.2	
DWTW	-Φ					2.8	0
DWTW	-F					11.4	35
Total		45.17					

Table 4.--Runoff summary - Crow Creek near Fairview, Wyoming

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1962	1920	1080	1670	1840	1990	1850	6730	10320	5900	3650	2920	2460
1963	2750	2560	2390	2140	3960	3030	4090	6590	6070	3670	2570	2780
1964	2570	2820	2330	1720	1600	2010	3960	10470	9860	5570	3880	3090
1965	3110	2940	3800	3280	2780	2730	6710	12320	10240	5510	4240	3890

Annual Runoff

Year	A-F	Inches
1962	42380	6.91
1963	42600	6.95
1964	49900	8.13
1965	61560	10.04
Ave.	49110	8.01

Three water years (1951-53) were simulated on Diamond Creek. The water balance computed for 6-day intervals during the average year is shown in Table 4.

An evaluation of the credibility of the simulated responses was made by comparing the simulation analysis with the only streamgage in the area (Crow Creek, near Fairview, Wyoming). The runoff summary from this watershed for 1962-65 is seen in Table 5. The data have similar characteristics, and until more local surface water and climatological data become available, we must tentatively conclude that the model adequately simulates the flow regime of Diamond Creek. Similar water balance simulation analysis have been performed on each of the watersheds listed in Table 2.

T : 4 ^ver anr wa' bal , D' nd C k, [redacted]ibo tio For Idaho.

DIAMOND CREEK,BLACKFOOT RIVER BASIN

WATER BALANCE SIMULATION

04/28/77 21.42.24.
AVERAGE OF YEARS 1951 - 1953

	CURRENT		INTERVAL TOTALS				YEAR TO DATE				
	SNOWPACK W. E.	RECHARGE REQ	PRECIP	INPUT	EVAPOTRANS FROM	GENERATED RUNOFF	PRECIP	INPUT	EVAPOTRANS	GEN RUNOFF	CHANGE IN RCHRG RQ
10 6	.20	-3.08	.58	.35	.1348	.05	.58	.35	.1348	.05	.03
10 12	.09	-2.96	.25	.35	.1608	.08	.83	.71	.2955	.13	.14
10 18	.19	-2.93	.25	.15	.1355	.00	1.08	.85	.4311	.13	.17
10 24	.34	-3.02	.19	.03	.1262	.01	1.27	.89	.5573	.13	.08
10 30	.57	-3.02	.37	.11	.1279	.00	1.64	.99	.6852	.14	.08
11 5	.75	-3.07	.19	0.00	.0600	0.00	1.83	.99	.7452	.14	.03
11 11	.95	-3.11	.22	0.00	.0537	0.00	2.05	.99	.7990	.14	-.00
11 17	1.74	-3.12	.84	0.00	.0647	0.00	2.89	.99	.8637	.14	-.02
11 23	2.25	-3.14	.53	0.00	.0432	0.00	3.42	.99	.9069	.14	-.03
11 29	2.34	-3.15	.11	0.00	.0276	0.00	3.53	.99	.9344	.14	-.05
12 5	3.12	-3.16	.81	0.00	.0522	0.00	4.34	.99	.9866	.14	-.06
12 11	3.03	-3.17	.56	0.00	.0409	0.00	4.90	.99	1.0275	.14	-.07
12 17	3.93	-3.19	.31	0.00	.0329	0.00	5.21	.99	1.0604	.14	-.08
12 23	4.49	-3.19	.61	0.00	.0410	0.00	5.82	.99	1.1014	.14	-.09
12 29	4.01	-3.20	.12	0.00	.0240	0.00	5.94	.99	1.1254	.14	-.10
1 4	4.94	-3.21	.36	0.00	.0309	0.00	6.30	.99	1.1563	.14	-.11
1 10	5.23	-3.21	.32	.01	.0324	0.00	6.62	1.00	1.1887	.14	-.11
1 16	5.99	-3.21	.81	0.00	.0538	0.00	7.44	1.00	1.2425	.14	-.11
1 22	7.37	-3.21	1.46	0.00	.0761	0.00	8.89	1.00	1.3185	.14	-.11
1 28	7.82	-3.22	.48	0.00	.0461	0.00	9.37	1.00	1.3646	.14	-.12
2 3	8.57	-3.23	.83	0.00	.0656	0.00	10.20	1.00	1.4302	.14	-.12
2 9	9.35	-3.23	.86	0.00	.0943	0.00	11.06	1.00	1.5245	.14	-.12
2 15	9.46	-3.21	.18	.01	.0571	0.00	11.24	1.01	1.5816	.14	-.11
2 21	10.06	-3.20	.69	.01	.0713	0.00	11.92	1.02	1.6529	.14	-.10
2 27	10.26	-3.20	.25	0.00	.0616	0.00	12.18	1.02	1.7144	.14	-.10
3 4	10.55	-3.20	.42	0.00	.0912	0.00	12.60	1.02	1.8056	.14	-.10
3 10	10.63	-3.20	.39	0.00	.1146	0.00	12.99	1.02	1.9202	.14	-.10
3 16	11.10	-3.20	.38	0.00	.1064	0.00	13.37	1.02	2.0266	.14	-.10
3 22	11.72	-3.20	.74	0.00	.1269	0.00	14.11	1.02	2.1535	.14	-.10
3 28	12.17	-3.20	.60	0.00	.1486	0.00	14.71	1.02	2.3021	.14	-.10
4 3	12.21	-3.17	.27	.07	.1578	.04	14.98	1.09	2.4599	.17	-.07
4 9	12.12	-3.09	.28	.17	.2074	.08	15.26	1.26	2.6672	.25	.02
4 15	12.32	-3.05	.60	.17	.2238	.13	15.85	1.44	2.8910	.38	.06
4 21	12.10	-2.86	.41	.38	.2565	.18	16.26	1.82	3.1475	.56	.24
4 27	11.11	-2.48	.13	.84	.3445	.40	16.39	2.66	3.4920	.96	.62
5 3	10.02	-2.16	.41	1.23	.2991	.86	16.78	3.89	3.7911	1.82	.94
5 9	8.01	-1.98	.15	1.28	.4386	.94	16.93	5.17	4.2297	2.77	1.13
5 15	7.94	-1.81	.29	.75	.3970	.39	17.22	5.91	4.6267	3.16	1.29
5 21	7.47	-1.47	.76	.93	.4816	.40	17.98	6.84	5.1083	3.56	1.63
5 27	6.56	-1.08	.62	1.29	.3707	.77	18.60	8.13	5.4850	4.33	2.02
6 2	5.30	-.84	.37	1.45	.4258	.96	18.97	9.59	5.9108	5.29	2.26
6 8	4.15	-.82	.44	1.43	.5253	1.05	19.41	11.03	6.4361	6.34	2.28
6 14	3.02	-1.01	.11	1.05	.7861	.64	19.52	12.08	7.2222	6.98	2.09
6 20	2.25	-1.44	0.00	.65	.7691	.44	19.52	12.72	7.9912	7.42	1.66
6 26	1.81	-1.59	.43	.78	.6523	.37	19.95	13.50	8.6440	7.78	1.51
7 2	1.46	-2.14	.04	.30	.7117	.22	19.99	13.80	9.3557	8.01	.96
7 8	.99	-2.59	0.00	.37	.7110	.20	19.99	14.16	10.0669	8.21	.52
7 14	.46	-2.61	.35	.84	.5441	.36	20.33	15.00	10.6109	8.57	.49
7 20	.17	-2.78	.24	.51	.4993	.19	20.57	15.51	11.1102	8.76	.32
7 26	.02	-3.15	.03	.18	.4555	.09	20.60	15.70	11.5658	8.85	-.04
8 1	0.00	-3.11	.43	.44	.3903	.03	21.03	16.15	11.9561	8.88	-.01
8 7	0.00	-3.14	.54	.54	.5060	.07	21.57	16.69	12.4621	8.95	-.04
8 13	0.00	-3.54	.00	.00	.3979	0.00	21.57	16.69	12.8601	8.95	-.44
8 19	0.00	-3.78	.02	.02	.2580	0.00	21.59	16.71	13.1181	8.95	-.67
8 25	0.00	-3.75	.24	.24	.2179	0.00	21.83	16.95	13.3360	8.95	-.65
8 31	0.00	-3.72	.24	.24	.2036	.00	22.07	17.19	13.5395	8.95	-.62
9 6	0.00	-3.79	.06	.06	.1320	0.00	22.13	17.25	13.6716	8.95	-.69
9 12	.03	-3.82	.11	.07	.1037	0.00	22.24	17.32	13.7753	8.95	-.72
9 18	0.00	-3.74	.16	.19	.1171	0.00	22.40	17.51	13.8924	8.95	-.64
9 24	0.00	-3.85	.01	.01	.1170	0.00	22.41	17.52	14.0094	8.95	-.75
9 30	0.00	-3.90	.04	.04	.0903	0.00	22.45	17.56	14.0997	8.95	-.80

CHAPTER 5

REGIONALIZATION OF SIMULATED HYDROLOGIC RESPONSES

Handbook techniques for predicting hydrologic responses to vegetation manipulation are best presented on a regionalized basis. In these guidelines, criteria for regionalization are based on the interaction between precipitation, climate, geology and soils, and forest cover composition and density. These processes and their interactions have already been discussed in some detail, and an example has been given to show how a hydrologic model can be used to synthesize the hydrology of a given watershed. The hydrologic responses generated by the model were used to develop the regional analysis procedure.

Regionalization requires a certain amount of parameter lumping. Accordingly, the model-derived functions proposed in these guidelines isolate and express only the effects of aspect, soil depth, position in the watershed, and a forest cover density parameter. Effects of forest cover manipulation are determined through modification of the vegetation parameter holding other factors (aspect, soil characteristics, soil depth, and watershed position) constant.

Regional Evapotranspiration

The impacts of vegetation manipulation on evapotranspiration processes are determined through modification of baseline regional evapotranspiration. This is accomplished using modifier coefficients which are presented as functions of forest cover density. Forest cover density, an independent variable, can be directly translated into basal area, and hence the type of vegetation manipulation employed. Again, these response

functions were developed from data sets characteristic of the Rocky Mountain/Inland Intermountain Subalpine Zone (Table 2). The baseline hydrology of these watersheds was first simulated, then forest cover density was sytemmatically altered in the model to reflect forest cover changes ranging from partial to total removal of forest vegetation.

Although all of the major hydrologic processes were simulated, only those responses needed as inputs to the erosion and channel processes portions of these guidelines are presented. These include evapotranspiration, soil water, and water excess amount and distribution.

Seasonal Evapotranspiration

In these guidelines, evapotranspiration is calculated for each of three seasons. Thus,

$$\text{Annual ET} = \Sigma ET_i \qquad [40]$$

for a given hydrologic subunit. Hydrologic subunits are stratified according to aspect, average elevation, forest cover density, and soil water characteristics.

In summation form:

$$\text{Annual ET} = \varepsilon_1(ET_1) + \varepsilon_2(ET_2) + \varepsilon_3(ET_3) \qquad [41]$$

where ε_1 = modifier coefficients that vary with forest cover density (ε_1 = 1.0 for a condition of complete hydrologic utilization of the subunit by mature forest cover).

In these guidelines, the seasonal evapotranspiration is presented for three increments of time as follows:

winter:	Oct. 1 - Feb. 28,
spring:	March 1 - June 30, and
summer and fall:	July 1 - Sept. 30.

Analysis of several hundred station years of record simulated by the Subalpine Water Balance Model for perhaps 100 subunits in the Rocky Mountain/Inland Intermountain Region has shown that seasonal evapotranspiration varies with precipitation as shown by the relationships plotted on Figure 20.

The October 1 through February 28 interval is not precipitation dependent, since losses are essentially from interception and evaporation from the snow surface. These losses are aspect dependent as seen in Figure 20(a). Evapotranspiration losses during the March 1 - June 30 vary with precipitation below about 12 inches, and also depend on aspect. No aspect dependence was found for evapotranspiration losses during the July 1 - September 30 interval as seen in Figure 20(c). While soil depth is a factor in affecting evapotranspiration losses, this effect could not be demonstrated regionally.

Snow Accumulation and Redistribution

A consideration of important significance in the Rocky Mountain/ Inland Intermountain Region is the effect of watershed position as it relates to local snow accumulation, and thus the precipitation regime. Any alteration in forest vegetation will modify this regime, and hence the baseline ET as shown in Figure 20.

NOTE:

These curves must be considered as Preliminary and subject to revision as new data become available.

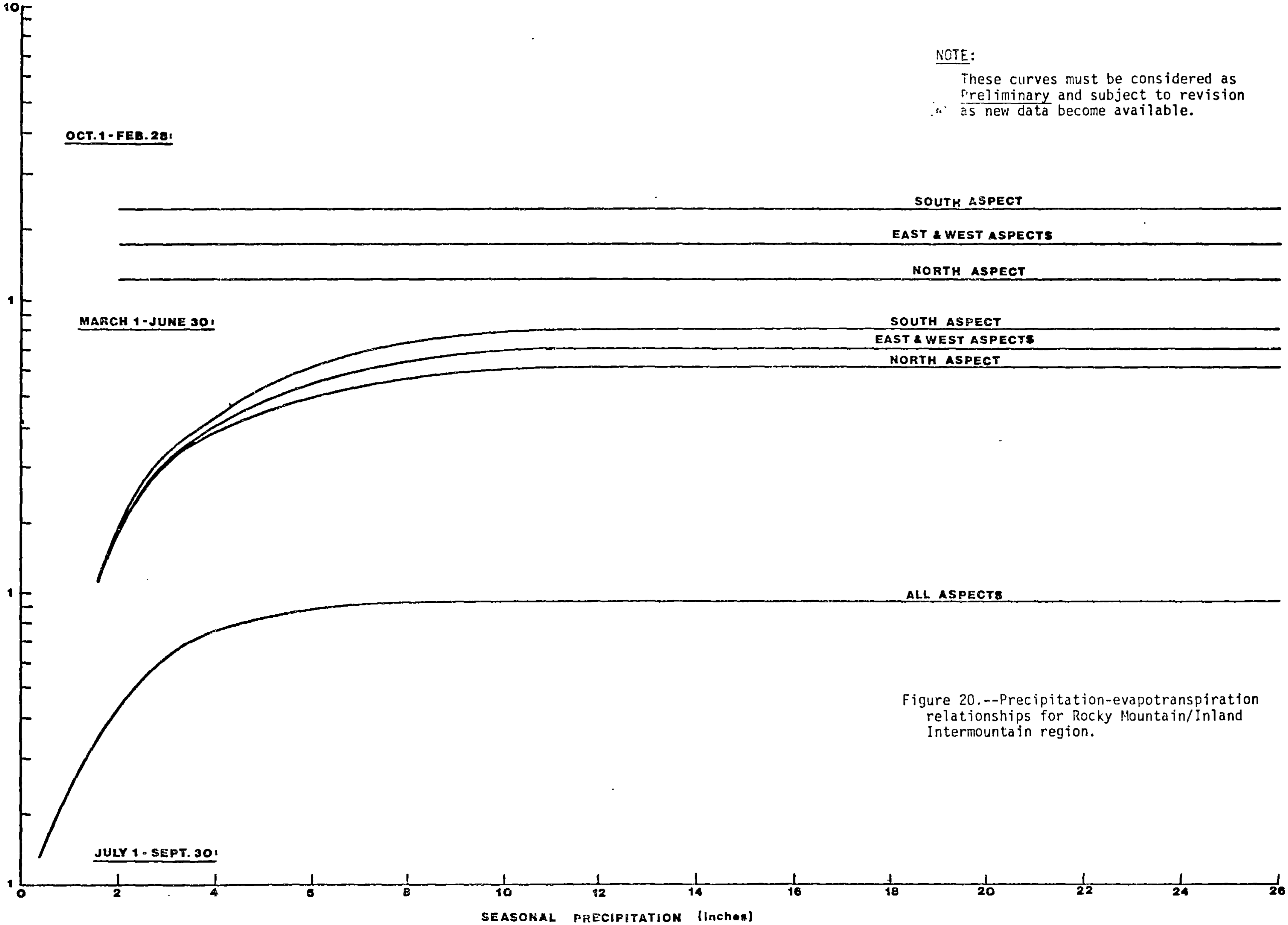


Figure 20.--Precipitation-evapotranspiration relationships for Rocky Mountain/Inland Intermountain region.

Local Water Balance

Equation [41] is the basis for computing the local water balance for a hydrologic subunit which is completely utilizing available water (maximum forest cover density), with no effect of past disturbance. If forest manipulation is contemplated on a previously disturbed area, the present hydrologic impact of the prior treatment must be determined before determining impacts from any proposed activity. Techniques for making the appropriate adjustments to the baseline relationships presented in Figure 20 are discussed below.

Evapotranspiration Modifier Coefficients

Figure 21 shows modifier coefficients (ε_i) which very according to forest cover density (C_d). Equation [41] involves application of the coefficients to ET for each of the three seasons to quantify hydrologic impacts resulting from reductions in forest cover density.

Soil Moisture Status

Baseline soil water requirements for conditions of full hydrologic utilization are plotted on Figure 22 for each of the three seasons discussed above. As with ET, changes in soil water status due to vegetation manipulation are estimated by means of modifier coefficients for each time interval as follows:

$$SW_i = Dp_i \cdot SW_i \qquad [42]$$

where SW_i = the baseline soil water status at the end of the ith interval (2/28, 6/30, and 9/30), and

Dp_i = regional modifier coefficient for soil water status.

Soil water modifier coefficients are plotted as functions of forest cover density in Figures 23 and 24. As with the Et coefficients, these coefficients are also stratified according to aspect.

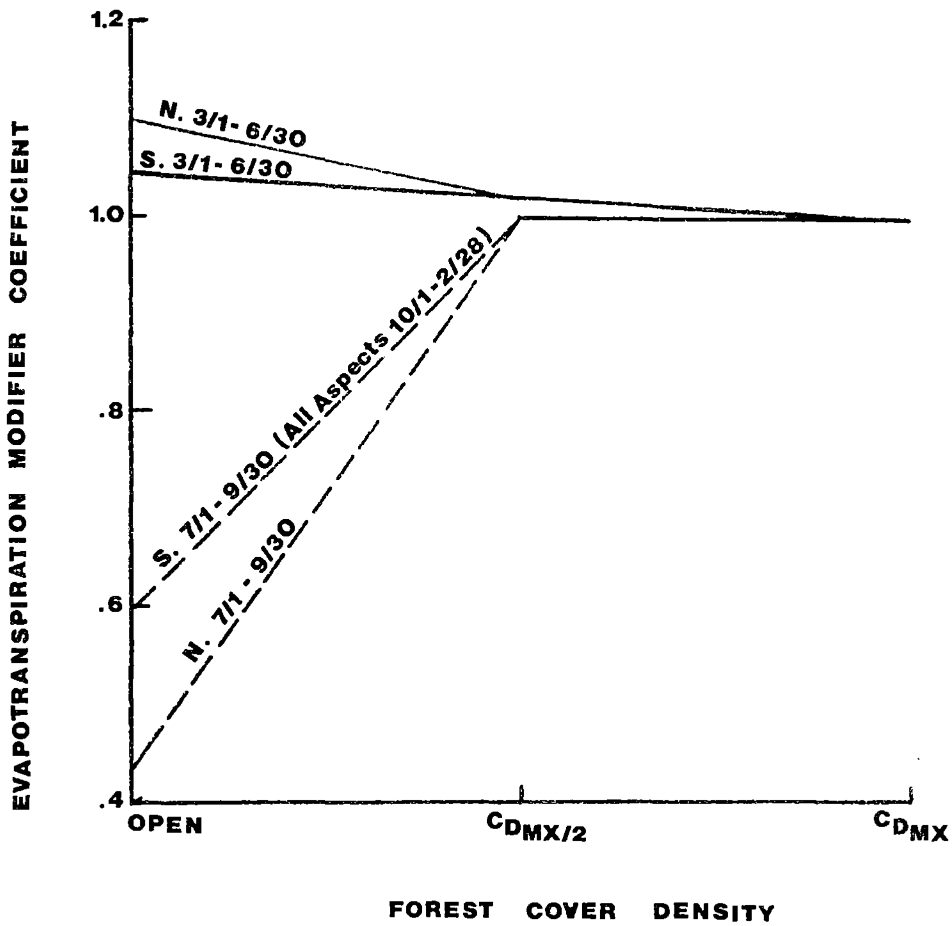


Figure 21.--Evapotranspiration change by decreases in cover density.

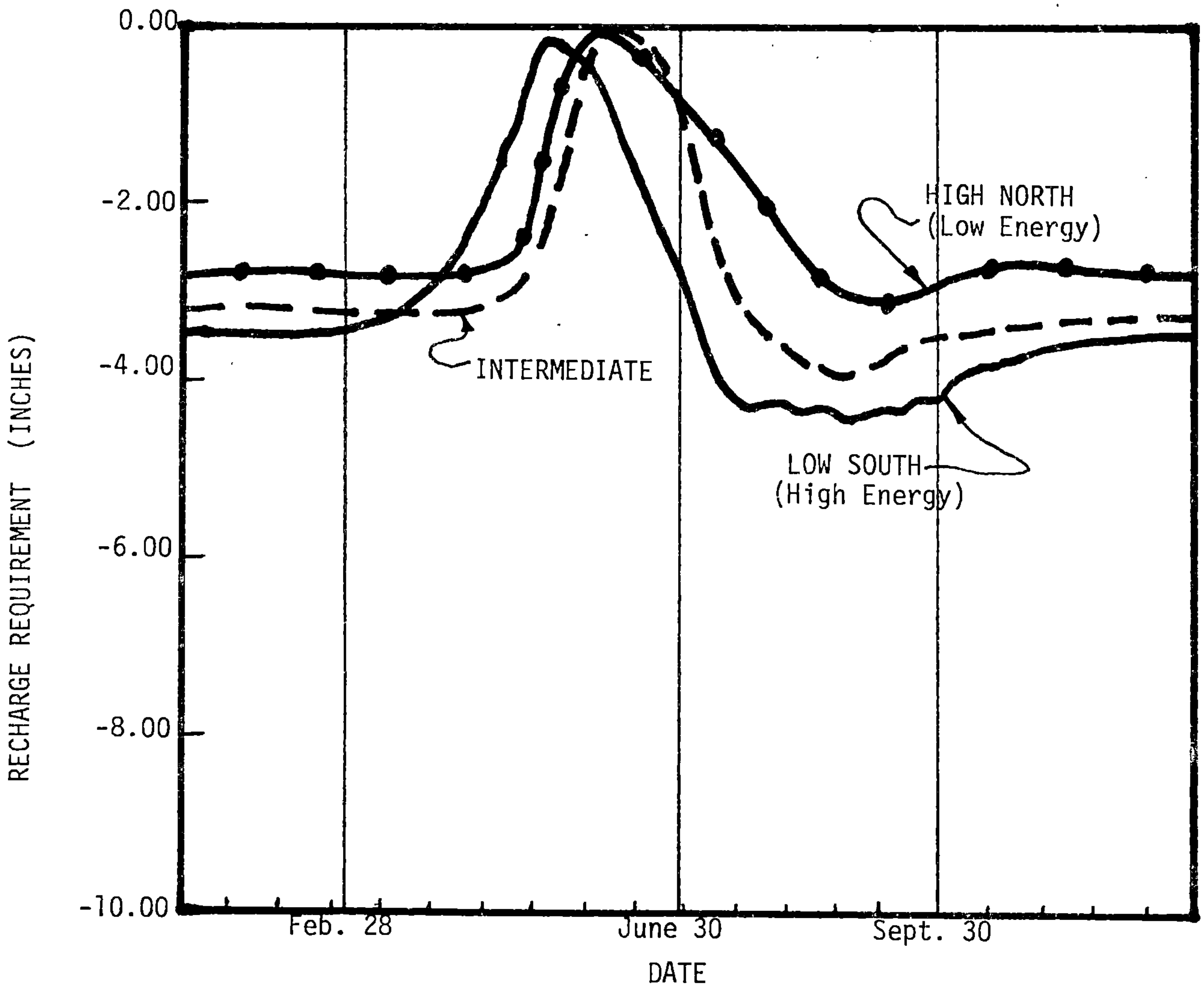


Figure 22.--Baseline soil water requirement relationships for the Rocky Mountain/Inland Intermountain region (moderate soil depth).

It should be noted that the baseline relationships plotted in Figure 22 represent recharge requirements for moderate-depth soils (approximately 5.5 inches of water holding capacity.) For deeper soils (water holding capacity greater than 10 inches), recharge requirements in Figure 22 should be multiplied by the following coefficients:

	Feb. 28	June 30	Sept. 30
High North	1.0	1.0	1.0
Intermediate	1.4	1.2	1.2
Low South	1.7	1.3	1.4

Adjustment coefficients for soils having between 5.5 and 10 inches water holding capacity can be approximated by interpolation.

Forest Cover Density

Forest cover density (C_d) is a key variable in these guidelines. It is a major descriptive parameter of the form, structure, and arrangement of forest vegetation, and therefore, its manipulation through total or partial removal of tree cover will cause varying hydrologic impacts by associated changes in energy balance, snow accumulation, evapotranspiration, etc. This parameter is also related to basal area--a unit of measurement commonly used in forest management.

As previously discussed, forest cover density as used in these guidelines is not defined as "canopy" or "crown" closure, but rather as a tree parameter which integrates the net affects of the overstory on the transmission of radiation to the forest floor. Forest cover density, and thus transmissivity coefficient, varies according to crown closure, vertical foliage distribution, species, season, age class, and stocking. It is assumed that the empirical relationship for transmissivity (equation [24]) applies to tree species in the Rocky Mountain/Inland Intermountain Subalpine Zone. Functions which relate C_{dmx} (forest cover density which results in complete hydrologic utilization; i.e., mature old-growth forest cover) are plotted in Figure 25 for spruce-fir, lodgepole pine, and ponderosa pine for stem diameters > 4 inches dbh.

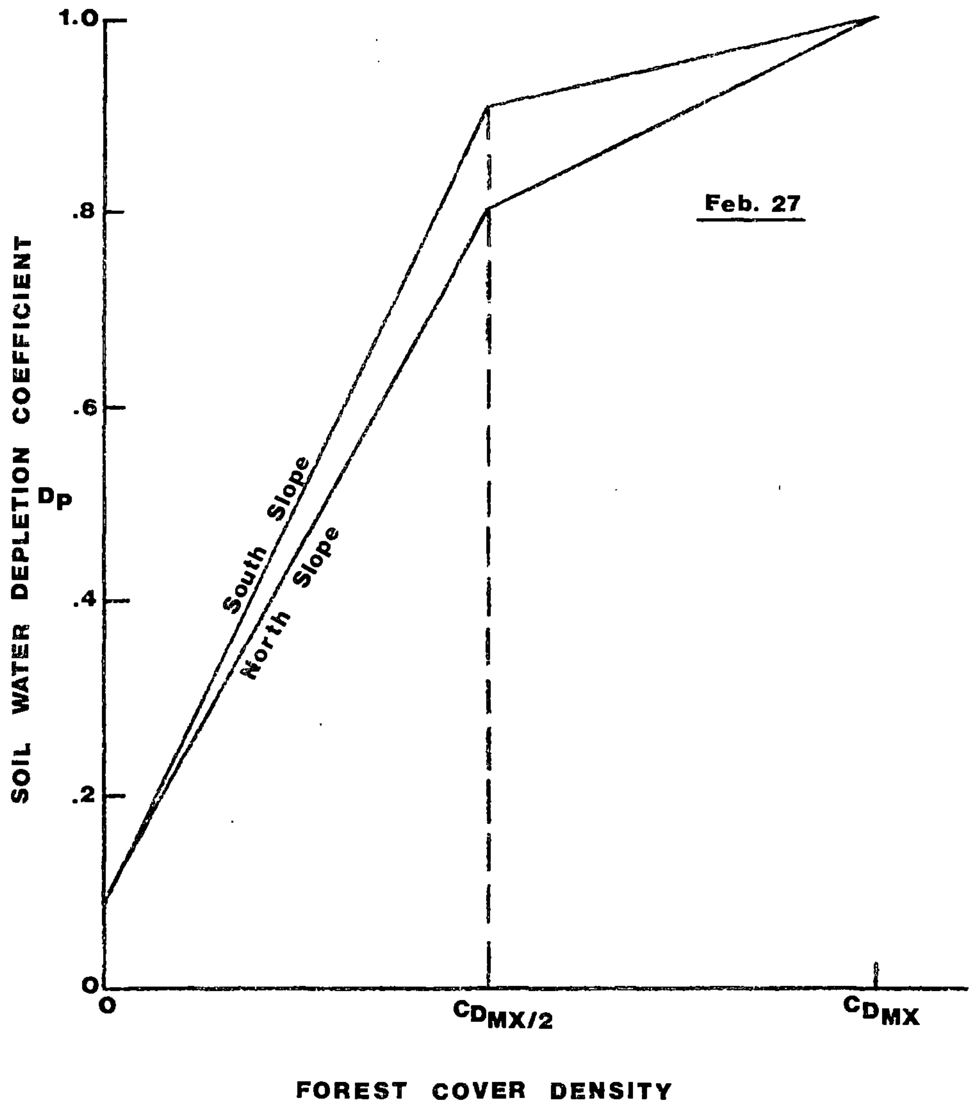
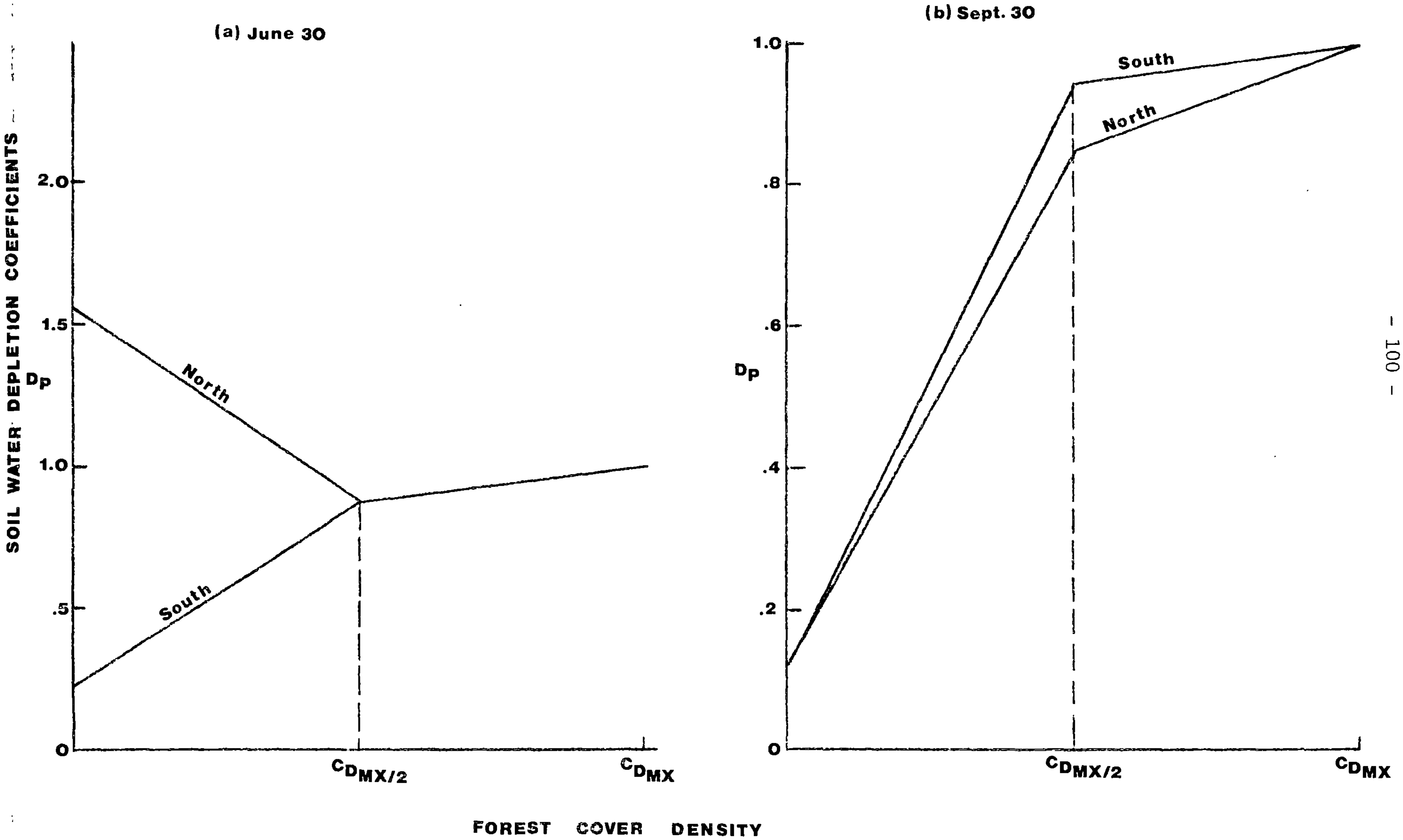


Figure 23.--Soil water modifier coefficient as a function of forest cover density for February 27.

Figure 24.-- Soil water modifier coefficient as a function of forest cover density for: (a) June 30, and (b) September 30.



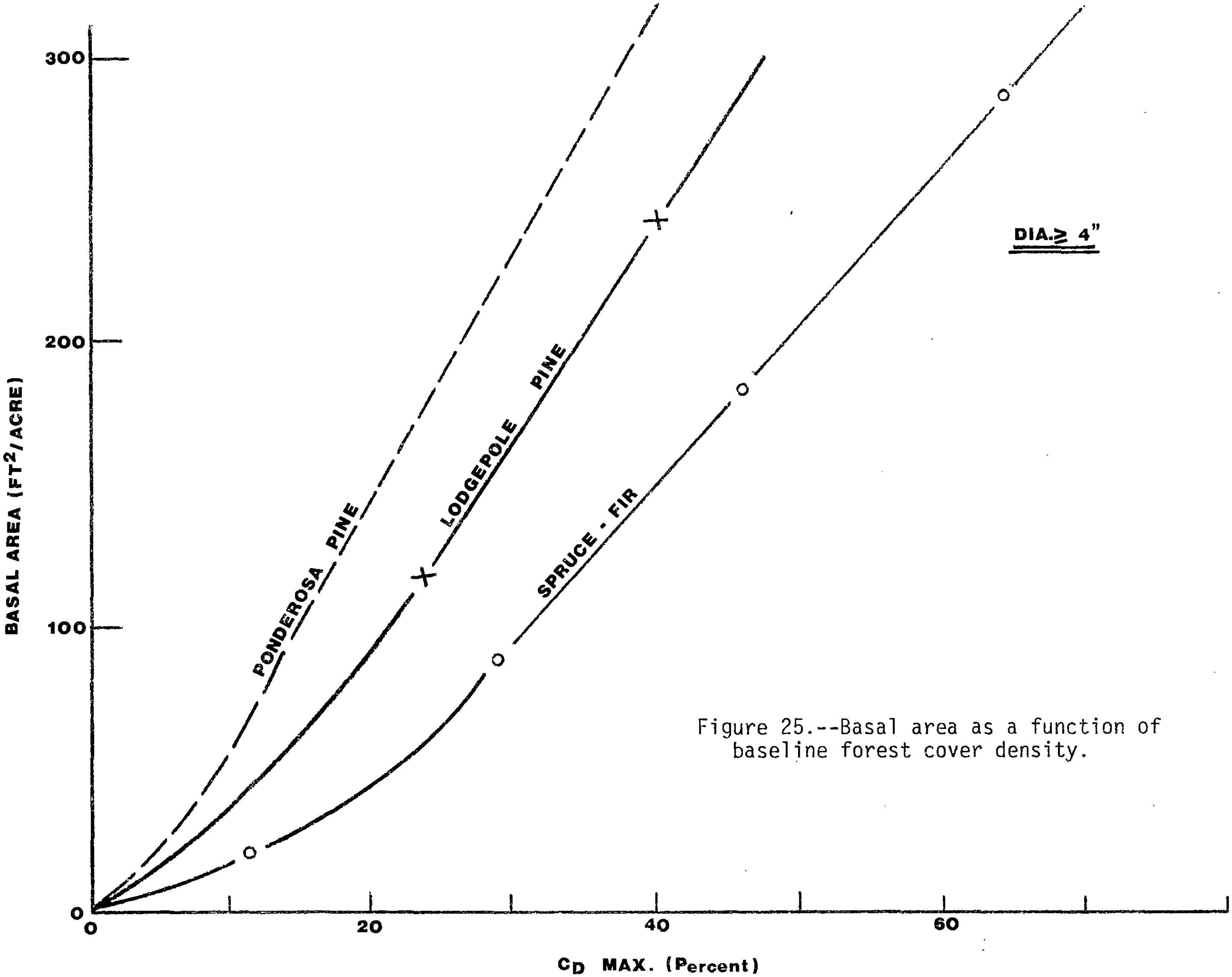


Figure 25.--Basal area as a function of baseline forest cover density.

Time Trends (Recovery)

Long-term hydrologic response evaluation must consider recovery of forest vegetation as it pertains to evapotranspiration, interception, reflectivity, and snow redistribution. The regional response curves and modifier coefficients presented in these guidelines can be modified as suggested in equations [25] and [37] to account for long-term changes in evapotranspiration and snow redistribution.

Water Yield Changes

Perhaps the most important output from the hydrologic analysis is the quantity and timing of water excess and associated changes produced by mining activities. This analysis is based on the hydrologic equation in which

$$Q_b = P - \Sigma ET_i \pm \Delta S \qquad [43]$$

in which Q_b = baseline water yield under conditions of maximum hydrologic utilization,

P = annual precipitation,

ΣET_i = the annual evapotranspiration discussed above, and

ΔS = annual change in watershed storage.

It is assumed that on first-order watersheds annual $\Delta S = 0$.

Mining activities can result in disturbances that vary from partial to total removal of forest vegetation. Accordingly, in most cases, regardless of precipitation form, satisfactory results can be obtained if equation [43] is rewritten as:

$$Q_{cutover} = (P + P_c) - ET_c \qquad [44]$$

and

$$Q_{undisturbed} = (P + P_u(- ET_u \qquad [45]$$

in which P_c = change in precipitation regime in cutover area (changes in snowpack accumulation),

P_u = change in precipitation regime in adjacent undisturbed areas,

ET_c = evapotranspiration in the cutover area, and

ET_u = evapotranspiration in the adjacent uncut forest.

Generally, both equations [44] and [45] will be used in making a hydrologic evaluation since open areas created as the result of mining activities will cause redistribution of the seasonal snowpack. The net effect then, on water yield is given by the equation:

$$Q = \gamma_c(Q_c) + \gamma_u(Q_u) \qquad [46]$$

in which γ_c = percent of the cutover area, and

γ_u = percent of the area left undisturbed.

Streamflow Timing

The characteristics of volume and timing of streamflow changes are both necessary inputs to evaluation of erosion and channel processes presented in Chapters 3 and 7 of these guidelines. One important assessment of the hydrologic impacts from mining activities concerns changes that are likely to occur in the distribution of water excess.

Determinations of changes in hydrograph characteristics are accomplished through 6-day distribution graphs of seasonal snowmelt runoff shown in Figures 26-29. These distribution graphs vary by aspect, and are present for both forested (baseline with C_{dmx}) and open areas. Treatment effects through forest cover manipulation on a given hydrologic subunit are demonstrated as a shift in the timing, base-length, and peak flow. The graphs were derived from simulation analyses of representative subunits within the watersheds presented in Table 2.

As seen in Figure 26, distribution graphs for several elevation zones and aspects may be combined. Three major categories are defined as:

1. High Energy Low Elevation Aspects
   a. low south
2. Intermediate Energy Aspects
   a. low to mid-elevation north
   b. low to mid-elevation east
   c. low to mid-elevation west
   d. high elevation south
3. Low Energy High Elevation Aspects
   a. high north
   b. high west
   c. high east

Position of runoff excess distribution on the time axis varies throughout the region. Accordingly, the approximate date of the onset of spring runoff must be known for a given watershed. It is assumed that the relative timing between aspects and elevations shown in Figure 26 applies to most watersheds in the region.

Figure 26.--WATER EXCESS DISTRIBUTION GRAPHS FOR ROCKY MOUNTAIN/INLAND INTERMOUNTAIN REGION - BASELINE

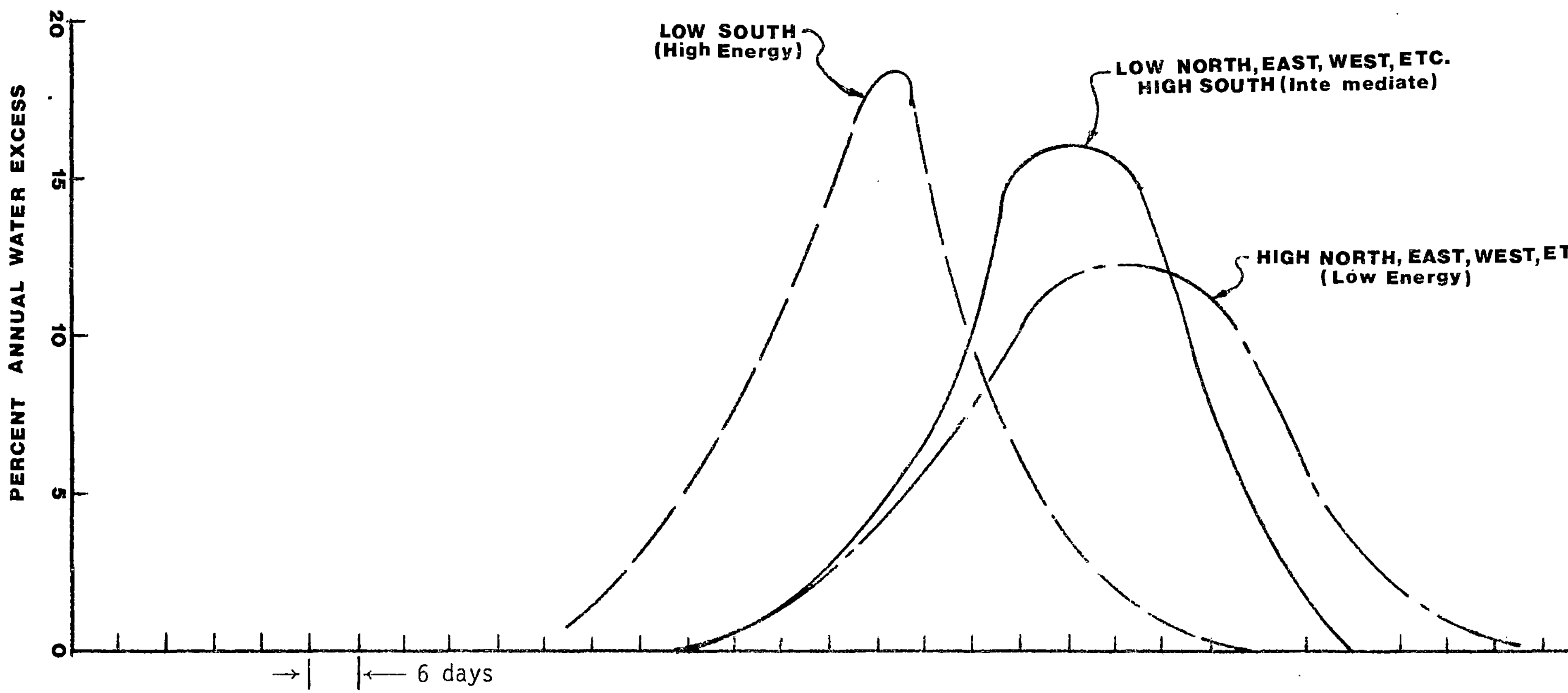


Figure 27.--WATER EXCESS DISTRIBUTION GRAPHS FOR LOW SOUTH SLOPE (HIGH ENERGY ASPECTS)

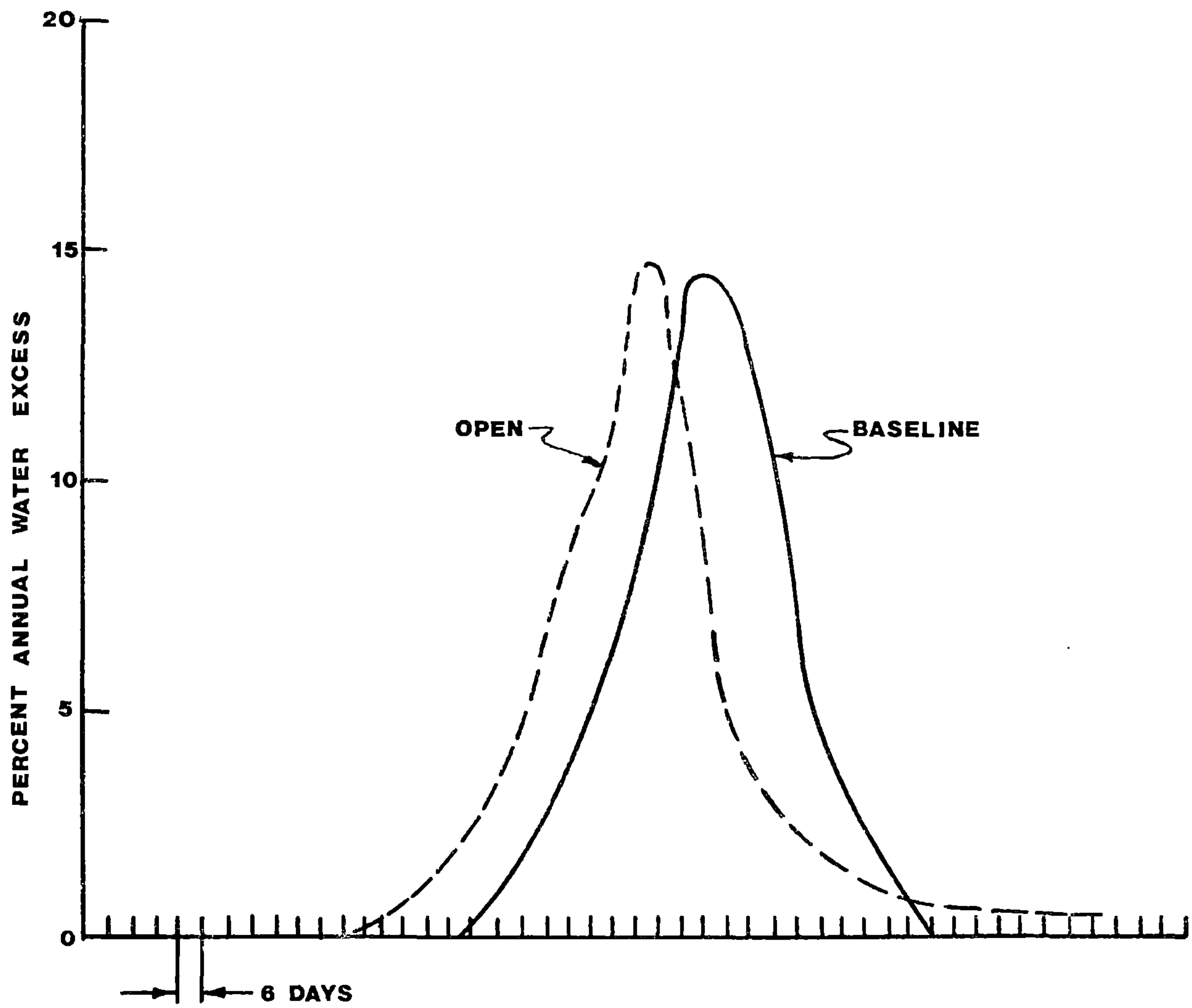


Figure 28.--WATER EXCESS DISTRIBUTION GRAPHS FOR INTERMEDIATE ENERGY ASPECTS

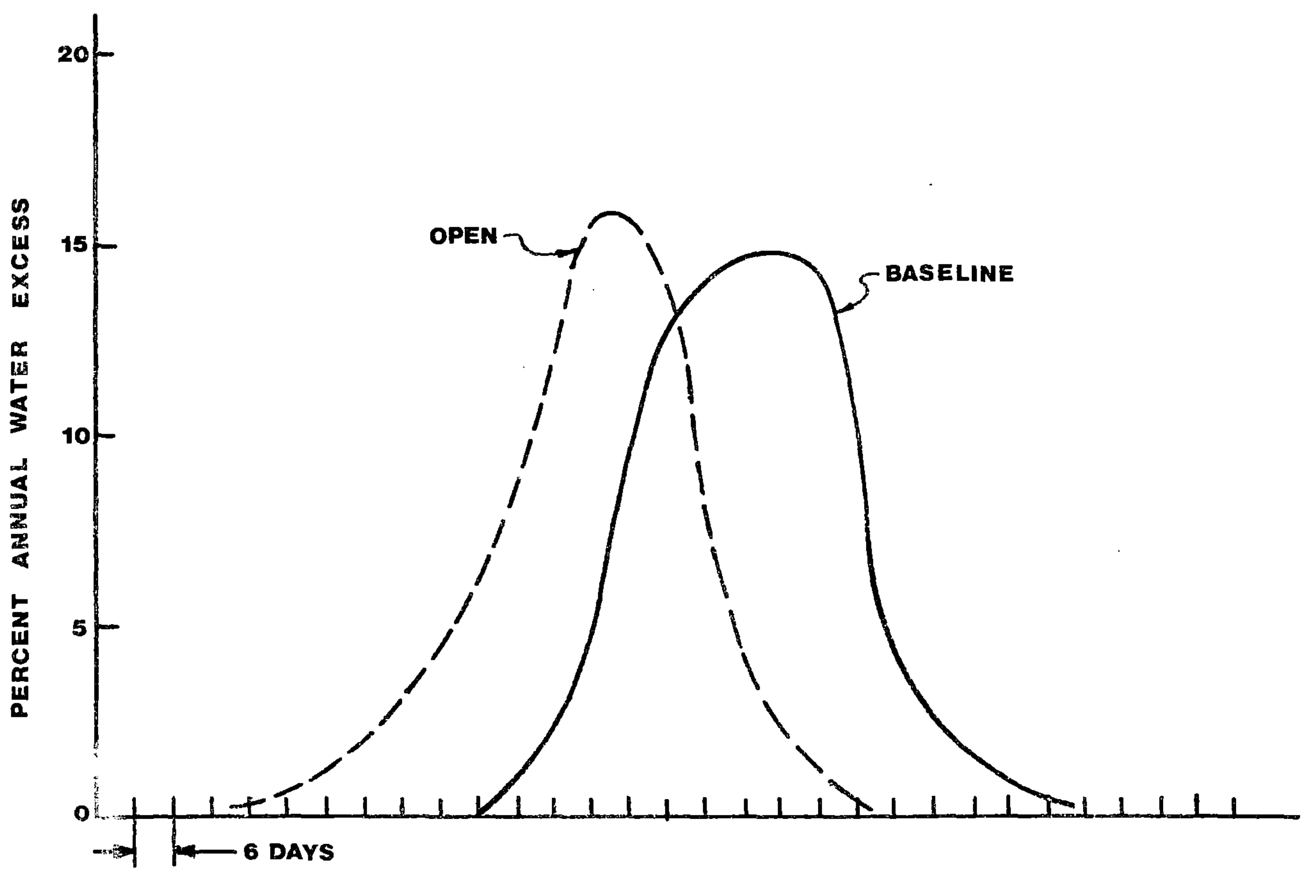
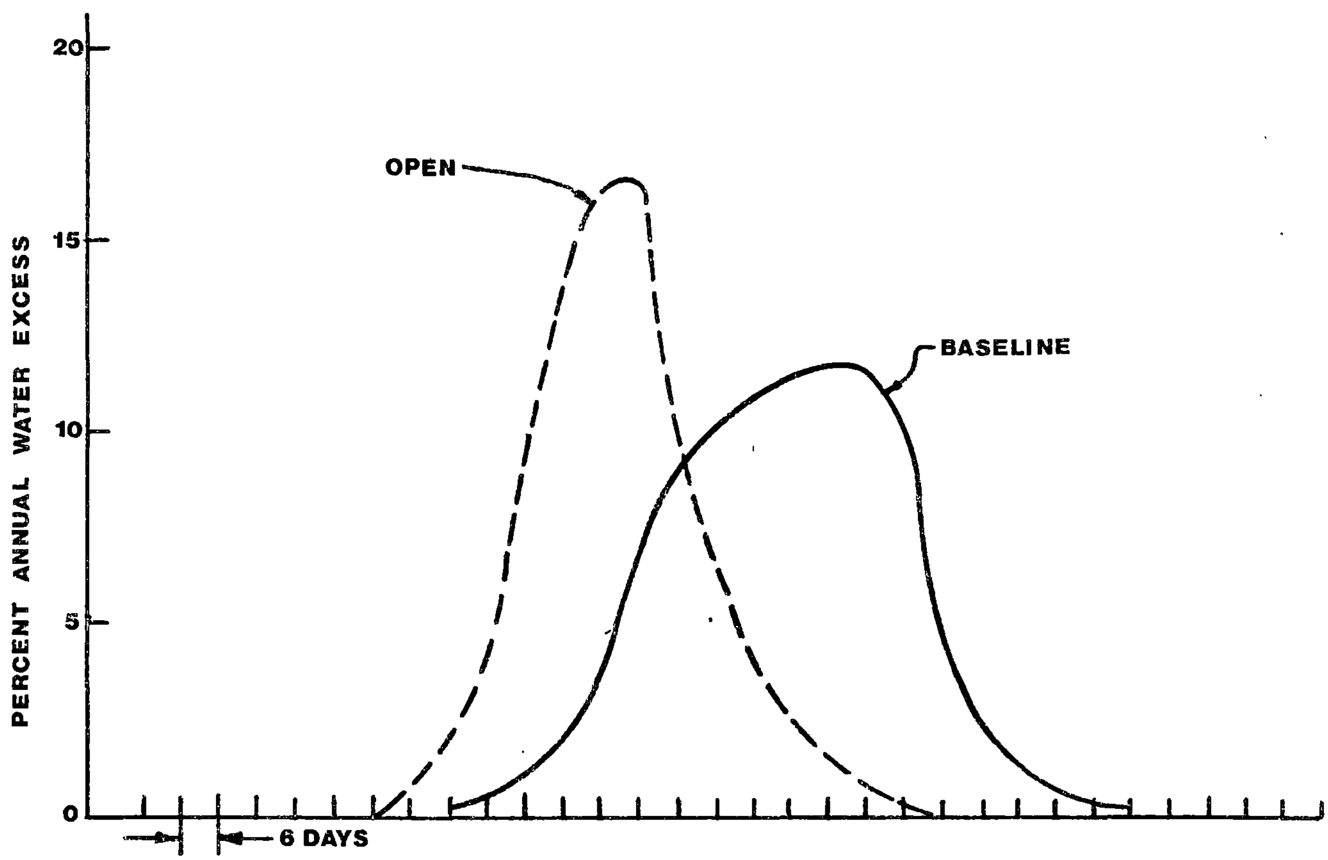


Figure 29.--WATER EXCESS DISTRIBUTION GRAPHS FOR LOW ENERGY ASPECTS



For purposes of these guidelines it can be assumed that peak water excess from open areas is generated 3 weeks earlier than from the forest (Figure 30), and are increased by approximately 3 percent. It may also be assumed that selective cutting will not change the distribution of water excess provided that forest cover density is not reduced more than 50 percent. Heavier reductions in forest cover density will accelerate the rate of water production. It is recommended that Figure 30 be used to adjust baseline distribution curve parameters to account for changes in distribution graph parameters caused by reductions in forest cover density ranging from 50 percent to complete removal. For C_d reductions < 50 percent, the baseline distribution graphs are used, whereas for C_d reductions > 50 percent, the distribution graphs for open areas are recommended using the appropriate modifier coefficients (Figure 30) for timing and peak, making appropriate corrections so that the area under the modified distribution graph is 100 percent.

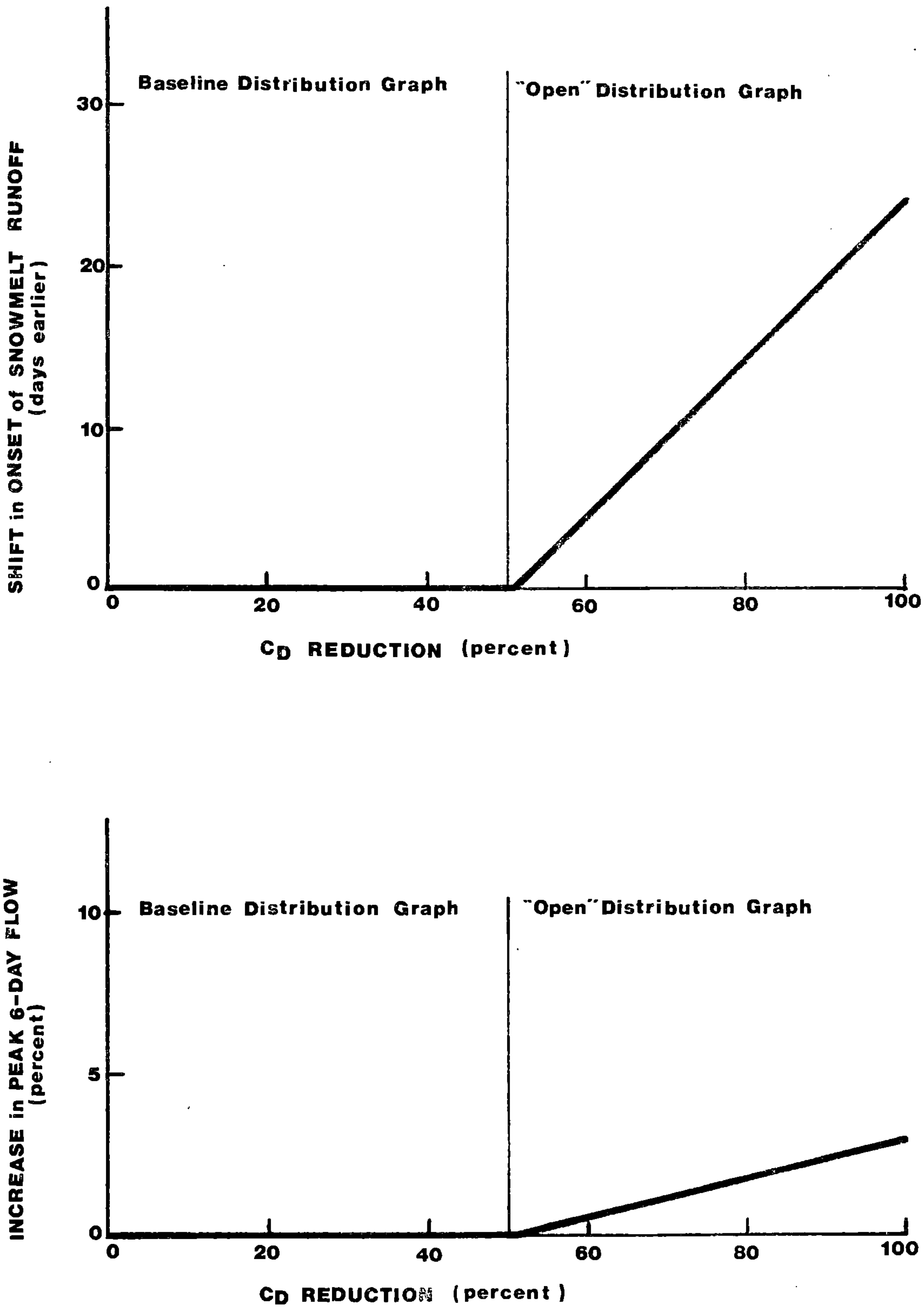


Figure 30.--Modifier coefficients for WATER EXCESS DISTRIBUTION GRAPHS FOR ALL ASPECTS.

CHAPTER 6

STORM RUNOFF PREDICTIONS

In many instances, hydrologic impacts on the storn runoff component of the annual hydrograph are required. Principles of the SCS method for estimating direct runoff from stormflow are summarized in these guidelines since: (1) it is applicable to ungaged watersheds, where at best, rainfall data are available on a daily basis from nonrecording gages, and (2) it is a standard and recognized engineering approach for predicting storm runoff (U.S. Soil Conservation Service, 1972).

It should be emphasized that if the method is used to determine hydrologic impacts from mining activities, care should be taken to relate the rainfall/runoff relationships to processes insofar as possible. Accordingly, the runoff curve number approach proposed in SCS and Forest Service manuals for making these evaluations is de-emphasized in favor of process hydrology previously discussed.

Theory

The following material is excerpted from Chapter 10 of Section A in the Soil Conservation Service National Engineering Handbook (1972). It summarizes the basic hydrologic principles that must be considered in evaluating storm runoff.

> If records of natural rainfall and runoff for a large storm over a small area are used, a plotting of accumulated runoff versus accumulated rainfall will show that runoff starts after some rain accumulates (there is an "initial abstraction" of rainfall) and that the double-mass line curves, becoming asymptotic to a straight line. On arithmetic graph paper and with equal scales the straight line has a 45-degree slope. The relation between rainfall and runoff can be developed from this plotting, but a better understanding of the relation is had by first studying a storm in which rainfall and runoff begin simultaneously (the initial abstraction does not occur).

For the simpler storm the relation between rainfall, runoff and retention (the rain not converted to runoff) at any point on the mass curve can be expressed as:

$$\frac{F}{S'} = \frac{Q}{P} \qquad [47]$$

where
F = actual retention
S' = potential maximum retention (S' F)
Q = actual runoff
P = potential maximum runoff (P Q)

Equation [47] applies to on-site runoff; for large watersheds there is a lag in the appearance of the runoff at the streamgage, and the double-mass curve produces a different relation. But if storm totals for P and Q are used equation [47] does apply even for large watersheds because the effects of the lag are removed.

The parameter S' in equation [47] does not contain the initial abstraction and differs from the parameter S to be used later. The retention S' is a constant for a particular storm because it is the maximum that can occur under the existing conditions if the storm continues without limit. The retention F varies because it is the difference between P and Q at any point on the mass curve or

$$F = P - Q \qquad [48]$$

Equation [47] can therefore be rewritten:

$$\frac{P - Q}{S} = \frac{Q}{P} \qquad [49]$$

Solving for Q produces the equation:

$$Q = \frac{P^2}{P + S'} \qquad [50]$$

which is a rainfall-runoff relation in which the initial abstraction is ignored.

The initial abstraction is brought into the relation by subtracting it from the rainfall. The equivalent of equation [47] becomes:

$$\frac{F}{S} = \frac{Q}{P - I_a} \qquad [51]$$

where I_a is the initial abstraction, F S, and Q (P - I_a). The parameter S includes I_a; that is, $S = S' + I_a$.

Equation [48] becomes:

$$F = (P - I_a) - Q \qquad [52]$$

equation [49] becomes:

$$\frac{(P - I_a) - Q}{S} = \frac{Q}{(P - I_a)} \qquad [53]$$

and equation [50] becomes:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad [54]$$

Equation [54] is the general rainfall-runoff relation with the initial abstraction taken into account. The initial abstraction is comprised of interception, infiltration, and surface storage, all of which occur before runoff begins. Each of these processes has been discussed previously in this handbook.

In computing storm runoff, it is assumed that a fraction of the potential maximum retention S, is the initial abstraction I_a, as the result of interception, infiltration, and detention storage. These components must be satisfied before runoff begins. The residual retention is primarily the infiltration which occurs after runoff begins. It is controlled: (1) by the rate of infiltration at the soil surface, or (2) by the rate of transmission through the soil mantle, or (3) by the water-holding capacity of the soil mantle, whichever is the limiting factor. The SCS Handbook (SCS, 1972) discusses the relationship of these processes to a succession of rainfall events as follows:

> A succession of storms, such as one a day for a week, reduces the magnitude of S each day because the limiting factor does not have the opportunity to completely recover its rate or capacity through weathering, evapotranspiration, or drainage. But there is enough recovery, depending on the soil-cover complex, to limit the reduction. During such a storm period the magnitude of S remains virtually the same after the second or third day even if the rains are large so that there is, from a practical viewpoint, a lower limit to S for a given soil-cover complex. Similarly there is a practical upper limit to S, again depending on the soil-cover complex, behond which the recovery cannot take S unless the complex is altered.

Many of the processes discussed above have been presented in some detail in these guidelines. All have been expressed in terms of parameters that are modified by mining activities. The solution of equation [54] for baseline conditions, and for conditions resulting from mining activities, will give the analyst an indication of the impact of that activity or control on runoff.

If, in equation [54], it is assumed that the soil water-holding capacity limits S, and $I_a = 0.2S$, then

$$Q = \frac{(P - {}^{R_c}/_{4})^2}{(P + R_c)} \qquad [55]$$

where $\quad {}^{R_c}/_{4} \leq P$, and

R_c = the soil water recharge requirement as previously described in these guidelines (Figure 22 and equation [42].

Additional discussion of the SCS method for generating storm hydrographs from direct runoff given by equation [55] for any design storm is presented in Appendix II.

CHAPTER 7

FIELD APPLICATION OF GUIDELINES

The equations summarized in Chapters 1 through 6 are based on technically sound engineering principles. With careful judgment, they can be used to provide a logical process-oriented basis for evaluating the impacts on erosion, channel processes, and sedument yield from mining activities in the Rocky Mountain/Inland Intermountain Region Subalpine Zone.

Again the reader is cautioned against a "cookbook" approach in using the equations and procedures proposed in these guidelines. The status of knowledge is still at a stage where a good deal of judgment and experience in this field are needed. During field application of the methods proposed herein, checks should be made on all intermediate results to be sure that they are reasonable. When they are available, field data should always be used as checks on the calculations.

The water yield and sediment prediction analysis presented next is designed to determine the potential changes in: (1) streamflow amounts and timing, and (2) sediment production changes associated with mining activities. The procedures are quantitative, and are designed to predict relative changes in the principal processes that influence water and sediment yield. They <u>are not</u> designed to predict absolute amounts, but to provide relative comparisons between baseline, current, and future hydrologic regimes in response to mining activities. They are tools that enable one to:

- Define management alternatives which, if implemented, will more favorably affect the water resource.
- Determine specific resource protection prescriptions to be applied, i.e., buffer strips, skidding methods, road density, cutting patterns in sensitive areas, etc.
- Evaluate effects from both past and future vegetative changes to assist in environmental planning.
- Provide a consistent, analytical framework with which to evaluate environmental impacts on the water resource as required in State and Federal environmental analysis reports associated with mining activities.

The regionalized functions for evapotranspiration, soil water regime, and water excess presented in Chapter 5 are the basis for field application of these guidelines. These relationships integrate the results from more than 30 years of watershed management research in the Rocky Mountain/Inland Intermountain Subalpine Zone. These results have been extended and regionalized by means of the Subalpine Water Balance Model (Leaf and Brink, 1973b. Accordingly, the basic relationships and modifier coefficients provide a high degree of flexibility in determining hydrologic impacts under most environmental conditions.

The analysis procedures do not require sophisticated computing devices, and are presented in outline format. The worksheets for this analysis were developed by David Rosgen, Hydrologist, Arapahoe-Roosevelt National Forest, R-2, in the course of conducting workshops on the evaluation of hydrologic impacts associated with silvicultural activities (Rosgen, 1977). Examples of site-specific data are presented for Middle Park, Colorado; however, the same kind of information is readily available in all subalpine areas within the cross-hatched area of Figure 1.

ANALYSIS PROCEDURE

Data Requirements

User Obtained

- Topog. maps 2" or 4"/mile
- Aerial photos
- Timber type map (species, age class, stocking)
- Timber basal area estimates
- Treatment history
  - Age of past cutting, insect damage, or fire
  - Acres involved in cutting or fire
  - Extent of basal area modification
- Maximum snowpack accumulation - water equivalent and date
- Precipitation - elevation curve
- Seasonal distribution of precipitation
- Basal area - Forest cover density curve
- Channel stability - sediment rating curve

Channel Stability Evaluation (Appendix III)

General Relationships and Data Furnished in Guidelines

Figure 8 - Channel stability - sediment rating curves (general).

Figure 13 - Snow redistribution curve and equations (Table 2-A; eq. [37a-b])

Figure 20 - Precipitation - evapotranspiration curve.

Figure 21 - Forest cover density - ET adjustment coefficients.

Figure 25 - Basal area - Forest cover density curves (general).

Figures 26-30 - Seasonal distribution of water excess by elevation/aspect season and modifier coefficient.

Equation [25] - Vegetative recovery by species for BA $<$ 50 ft^2/acre. (partial cutting)

Equation [38] - Vegetative recovery by species for BA $\geq$ 50 ft^2/acre (clearcutting).

Water Yield-Sediment Worksheet #1 (Rosgen, 1977)

Subdrainage:

Existing Condition

Acres: ______________

Dom. Aspect: ______________

Average elevation: ______________

Veg. Type: ______________

Ave.Class: ______________

Basal Area: ______________

Cover Density: ______________

Fire Dates, etc. and

% Area: ______________

____

____

Size of openings
in multiples of H: ______________

Channel
Stability
Rating: ______________

Peak Snowpack
Water Equiv.: ______________
(Table 6)
Date: ______________

Climatological Data
Precipitation:
10/1 - 2/28: ______________
3/1 - 6/30: ______________
7/1 - 9/30: ______________
Average annual: ______________

Proposed Condition

*Acres clear cut: ______________

% Total Area: ______________

**Diam. of clear cut
(T. height): ______________

Acres Partial Cut: ______________

% BA removed: ______________

New Forest Cover
Density: ______________

% Total Area: ______________

Snow Redistribution Coeff.: ______________
(Figure 13)

Evapotran. Adj. Coeff.: ______________
(Figure 20)

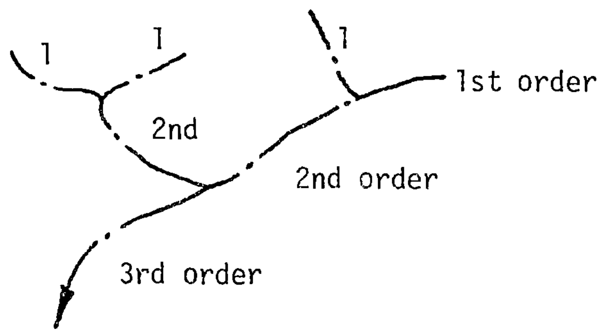
* Includes roads (acres/mile) + skid trails.

** Diameter of clearcut given in multiples of tree height (H).

Basic Analysis Procedure (Rosgen, 1977)

Water Yield

Step 1: Delineate subdrainage boundary
- no larger than 3rd order basin



- delineate by dominant aspect
- elevation range should not exceed 4,000 feet.

Step 2: Calculate weighted average elevation. Record dominant aspect. Calculate acres in subdrainage.

Step 3: From timber type map obtain:

- existing basal area (average)
- species composition
- age class distribution
- acres or % of area in clearcuts, insect damage, or wildfire burned, etc. and date of vegetative changes
- acres of roads (4 acres/mile)
- size of openings in diameter expressed as tree height (H), i.e., 5H = 300 ft. (if tree height = 60 feet)
- % BA removed for past partial cutting and year of treatment

Step 4: Calculate pretreatment (baseline) water balance.

- obtain mean annual precipitation from ppt/elevation curve (Figure 31). Determine seasonal distribution of precipitation (Figure 32).
- evapotranspiration (Figure 20)

Season	Precipitation	ET
10/1 - 2/28	Figure 31	Figure 20
3/1 - 6/30	Figure 31	Figure 20
7/1 - 9/30	Figure 31	Figure 20

Step 5: Calculate runoff (mean annual ppt.) - (mean annual ET)

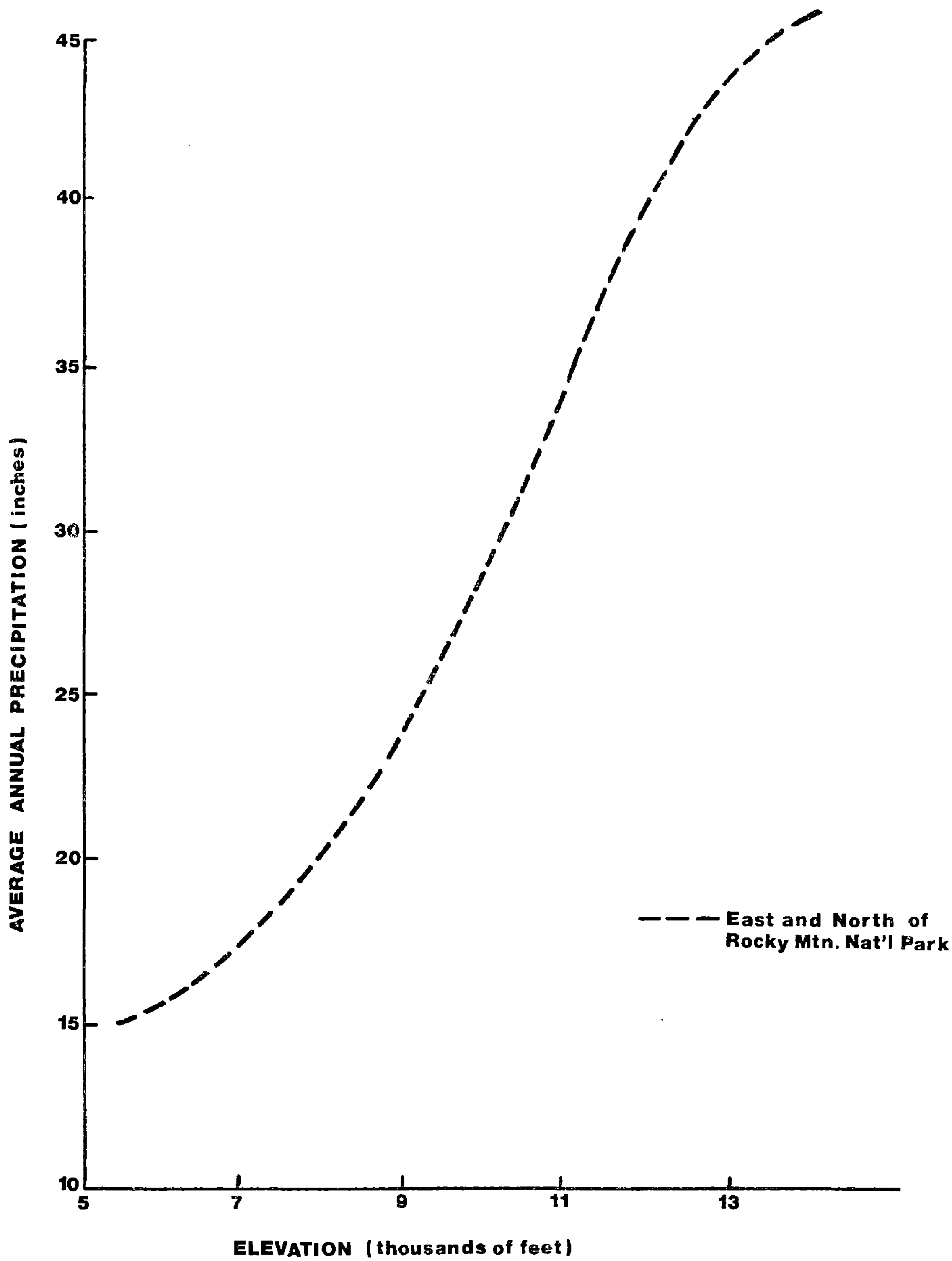


Figure 31.--Precipitation vs. elevation. (Rosgen, 1977)

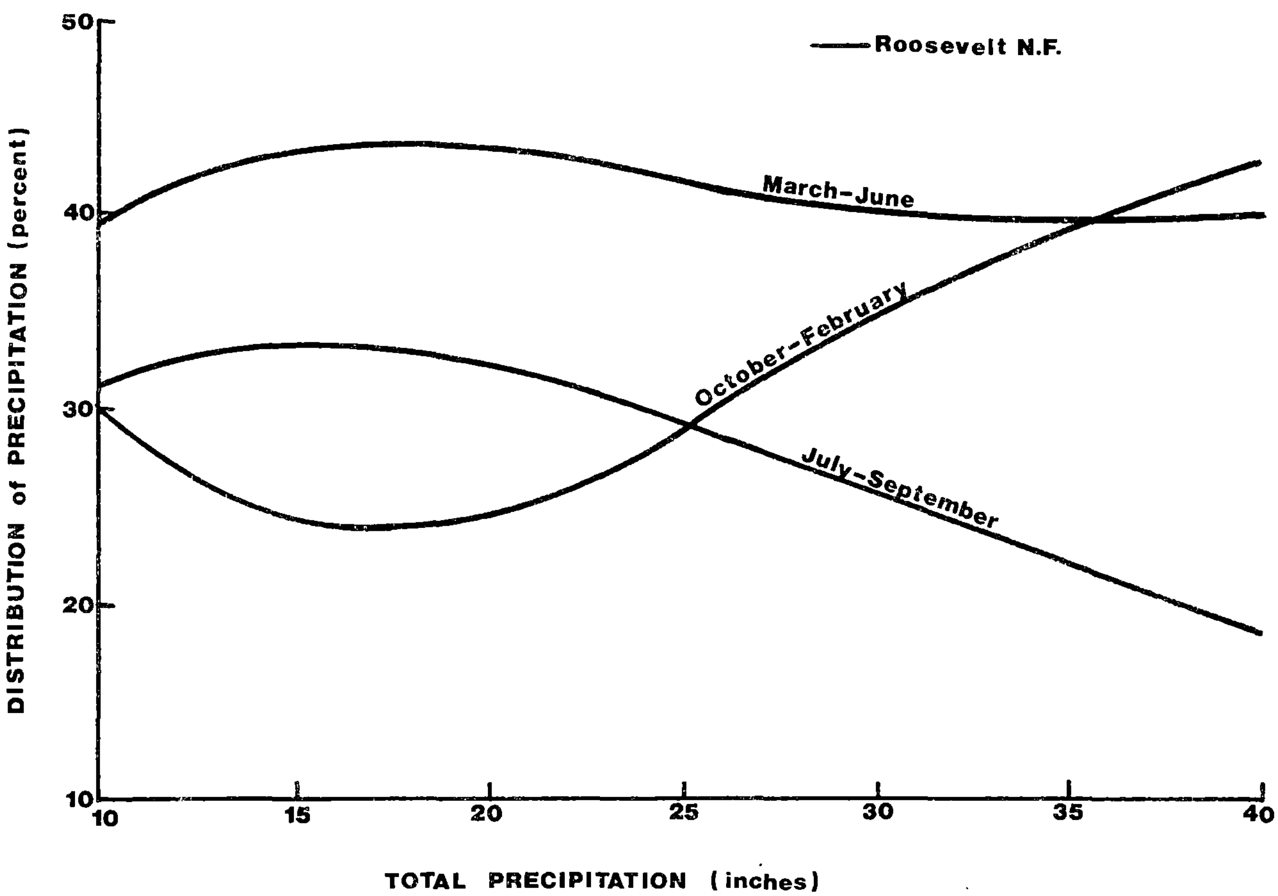


Figure 32.--Seasonal distribution of precipitation. (Rosgen, 1977)

Step 6: Plot pretreatment water excess distribution graph.

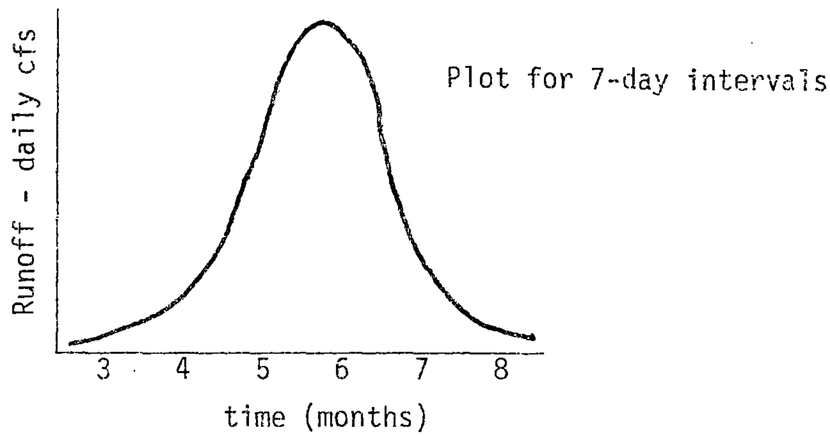
RO x % annual runoff for a 7-day average daily runoff period. (From "forested" condition - for appropriate elevation-aspect (Figure 26)).

$$\frac{\text{AI x acres}}{12} = \text{acre-feet}$$

1.98 acre-feet/day = 1 cfs

Divide 7-day cfs by 7 to obtain daily flow. Plot pretreatment water excess distribution graph.

Use worksheet #2 and plot column #3 of the worksheet.



Step 7: Determine hydrologic effects of past treatments (or if pristine, proposed treatments).

A. Snow Redistribution

determine diameter of openings as a function of tree height
if regrowth is 2/3 of adjacent stand height, disregard redistribution factor
obtain snow redistribution factor (ρ) from Figure 11
multiply (ρ) x maximum accumulation water equivalent in snowpack (Table 6)*

Snow WE_{max} x ρ = for open

Subtract an equal amount from forested = adj. Forest WE x WE_{max}) = for forested stand

i.e., if $\rho = 1.2$ and $WE_{max} = 18.2$

then 1.2 x 18.2 = 21.8" WE open
0.8 x 18.2 = 14.6" WE forested

area - weight WE by % of area in openings
% of area forested x WE forest = area weighted WE
% of area open % WE open = $\frac{\text{area weighted WE}}{\text{total WE}}$

---

*Not required for water balance calculations (step 8)

Table 6.--Amount and date of peak snowpack water equivalent

(Example: Middle Park, Colorado)

Dominant Elevation	Dominant Aspect	Maximum Snowpack Water Equivalent(In.)	Date
High	North	16.3	4/27
High	South	16.7	4/3
High	East	14.8	4/21
High	West	14.4	4/21
Middle	North	15.6	4/27
Middle	South	14.0	4/3
Middle	East	11.0	4/15
Middle	West	10.9	4/15
Low	North	13.2	4/21
Low	South	10.4	5/3
Low	East	12.8	4/27
Low	West	11.0	4/27

Step 8: Water Balance Adjustment - Evapotranspiration

a) Recovery of evapotranspiration - use as a function of basal area recovery, as in equations [25] and [38] or Figures 36 and 37.
and

	BA	% area involved	Assoc. cover density	
Max. Pot. BA =	250		55	Use to obtain revised ET adjustment coefficient (Figure 21)
Following treatment BA =	75		25	
Present condition BA =	150		40	

b) Water balance calculation

	(1) P (PPT - forest) (orig. ppt. x ρ)	(2) (PPT - open) (orig. ppt. x ρ)	(3) (ET - forest (new ET from revised ppt.) (Figure 20)	(4) (ET - open) (new ET from revised ppt.) (Figure 20)		(5) (ET adjustment coefficient) (Figure 21)		(6) (4) x (5) (Revised ET - open)
10/1 - 2/28:					x		=	
3/1 - 6/30 :					x		=	
7/1 - 9/30 :					x		=	

c) Adjusted runoff - Forest

Column (1) - Column (3) = Annual Runoff (inches) forest x % area = area weighted total area inches runoff open
(PPT forest) (ET forest)

Adjusted runoff - Open

Column (2) - Column (6) = Annual Runoff (inches) open x % area = area weighted total area inches runoff open
(PPT (Revised ET)

Step 9: Index hydrograph plotting of existing and/or proposed conditions.

a) Using Worksheet #2

Multiply % timing change for appropriate elevation aspects (Figures 24-30) times water excess before being are weighted from step 8-c for both open and forested conditions. This yields a hydrograph of area inches for 7-day flows over time. Convert from area inches to feet:

$$\left(\frac{\text{acres x area inches}}{12} = \text{acre-feet}\right)$$

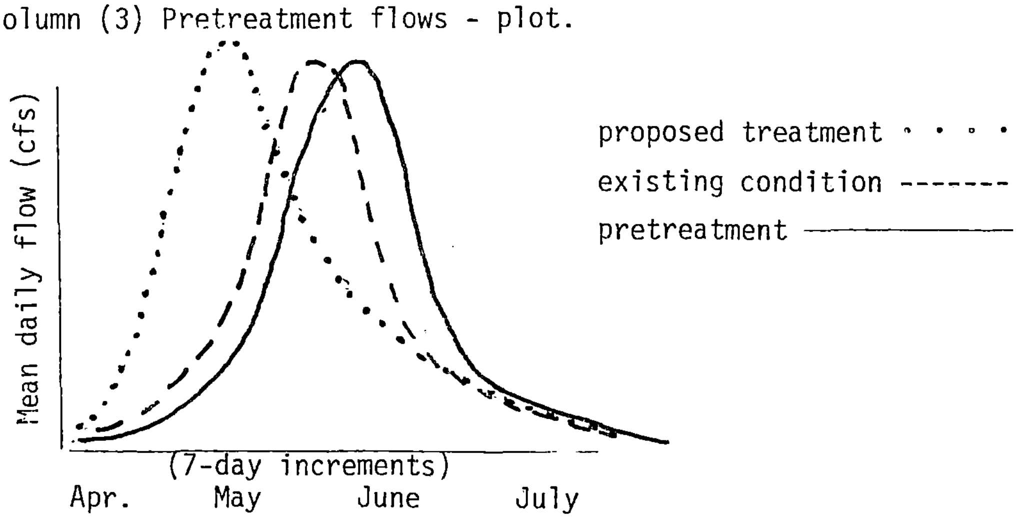
and then to daily cfs:

$$\left(\frac{\frac{\text{acre-feet}}{1.98}}{\text{7 days}}\right) = \text{daily cfs}$$

then plot on same as pretreatment hydrograph (step 6). Plot the sum columns #12 and #13 (forested) for existing condition and columns 14 (open) plus 15 (forested) for proposed condition.

b) Example of hydrograph plotting

- Column (3) Pretreatment flows - plot.



- Columns (12) + (13). Sum both for each 7-day increment for open and forested for existing conditions. - Plot.

- Columns (14) + (15). Sum both for each 7-day increment for both open and forested for proposed condition. - Plot.

WORKSHEET #2

WATER YIELD WORKSHEET

Subdrainage ________ % Elevation $\bar{x}$ ________
Aspect ________ Acres ________

Date	(1) (Figs) Annual % Adj.	(2) Pre-treatment Q in area in. (Col 1) x (Pre-treatment total runoff)	(3) Pre-treatment Q - daily cfs $\frac{(acres) \times (Col\ 2)}{12} \div 7$ / 1.98	(4) Existing Cond. Open Timing % Open x Total Area In. Q	(5) Existing Cond. Open Convert to daily cfs $\frac{(acres) \times (Col\ 4)}{12} \div 7$ / 1.98	(6) Existing Cond. Forested Timing % (Forested) x Total Area in. Q	(7) Existing Cond. Forested Convert to daily cfs $\frac{(acres) \times (Col\ 6)}{12} \div 7$ / 1.98	(8) Proposed Cond. Open Timing % Total x Total Area in. Q	(9) Proposed Cond. Open Convert to daily cfs $\frac{(acres) \times (Col\ 8)}{12} \div 7$ / 1.98	(10) Proposed Cond. Forested Timing % Total x Total Area in. Q	(11) Proposed Cond. Forested Convert to daily cfs $\frac{(acres) \times (Col\ 10)}{12} \div 7$ / 1.98	(12) Existing Cond. % area open	(13) Existing Cond. % area forested	(14) Proposed Cond. % area open	(15) Proposed Cond. % area forested	(16) Pre-treatment sediment cfs (mg/l) (Fig)
3/1																
3/8																
3/16																
3/24																
3/31																
4/7																
4/14																
4/21																
4/28																
5/5																
5/12																
5/19																
5/26																
6/2																
6/9																
6/16																
6/23																
7/7																
7/14																
7/21																
7/28																
8/5																
8/12																
8/19																
8/26																
					% of area x total Q = area wtd. Q		% of area x total Q = area wtd. Q		% of area x total Q = area wtd. Q		% of area x total Q = area wtd. Q					

SEDIMENT YIELD WORKSHEET

Date	(17) Tons/day (.0027 x cfs x mg/l) (Pre-treatment)	(18) Existing Cond. cfs mg/l Sum of Cols 12 + 13 (Fig)	(19) Tons/day (.0027 x cfs x mg/l) Existing Cond.	(20) Sum Cols. 14 + 15 Proposed Cond. cfs mg/l	(21) Proposed Cond. Tons/day (.0027 x cfs x mg/l)	(22) Tons/day x 7 Pretreatment	(23) Tons/day x 7 Existing	(24) Tons/day x 7 Proposed
3/1								
3/8								
3/16								
3/24								
3/31								
4/7								
4/14								
4/21								
4/28								
5/5								
5/12								
5/19								
5/26								
6/2								
6/9								
6/16								
6/23								
7/7								
7/14								
7/21								
7/28								
8/5								
8/12								
8/19								
8/26								
						Total tons sediment Pretreatment	Total tons sediment Existing Cond.	Total tons sediment Proposed Treatment

From Step 5 Pretreatment total runoff (area inches) ________ (All Forested)
From Step 8-C Existing condition total runoff (area inches) ________ Open
From Step 8-C Existing condition total runoff (area inches) ________ Forested
Proposed condition total runoff (area inches) ________ Open
Proposed condition total runoff (area inches) ________ Forested

Column 5 + Column 7 = Existing condition increased runoff total in cfs *
Area weighted Q totals

Column 9 + Column 11 = Proposed condition increased runoff in cfs **

* Should equal sum of Columns (12) + (13)

** Should equal sum of Columns (14) + (15)

To Plot Hydrographs:

Add Columns (12) + (13) and plot for each seven day period. This provides area weighted increments of Q for existing condition.

Add Columns (14) + (15) and plot for each seven day period. This provides area weighted increments of Q for proposal condition.

Step 10: Proposed Activity.

Follow identical procedure as in sections 3, 4, and 5 except ignore vegetative recovery relationships unless a projection for a 20-year+ cutting cycle may be needed.

Proposed treatment is a cumulative increase in yield adding pretreatment and existing condition hydrographs to the water yeild increase associated with proposed cutting.

If there has been no past logging activity, insect damage, or recent fires affecting Forest cover density, and/or snow redistribution, then the analysis is made using pretreatment and proposed treatment alone.

Sediment Yield Prediction Analysis

Data Needs:

(User obtains)	Sediment rating curve (Figure 33) or
(User obtains)	Channel stability rating (Appendix III)
(Provided)	Channel stability rating vs. sediment rating curves (Figure 34). To be used if sediment rating curves are not available.

Step 11:

a) Determine mg/l for each 7-day interval of daily cfs for pretreatment flows. Use Figure 33 or 34, whichever is available.

Using Worksheet #2:

b) Multiply pretreatment cfs for each 7-day increment times mg/l for that flow x .0027 = tons/day. i.e., (Column 3 x .0027 x mg/l, for each increment).

Using Worksheet #2:

c) Multiply sums of Columns (12) + (13) x the concentration of sediment associated with those cfs (Figure 38 or 39) x .0027 = tons/day for existing condition.

Using Worksheet #2:

d) Multiply sums of Columns (14) + (15) times the concentration of sediment (mg/l) for each 7-day increment times .0027 = tons/day for proposed treatment.

e) To determine total tons of sediment for pretreatment, existing, and proposed treatment:

Multiply each 7-day value of tons/day x 7. Sum each column for respective totals. See worksheet #2.

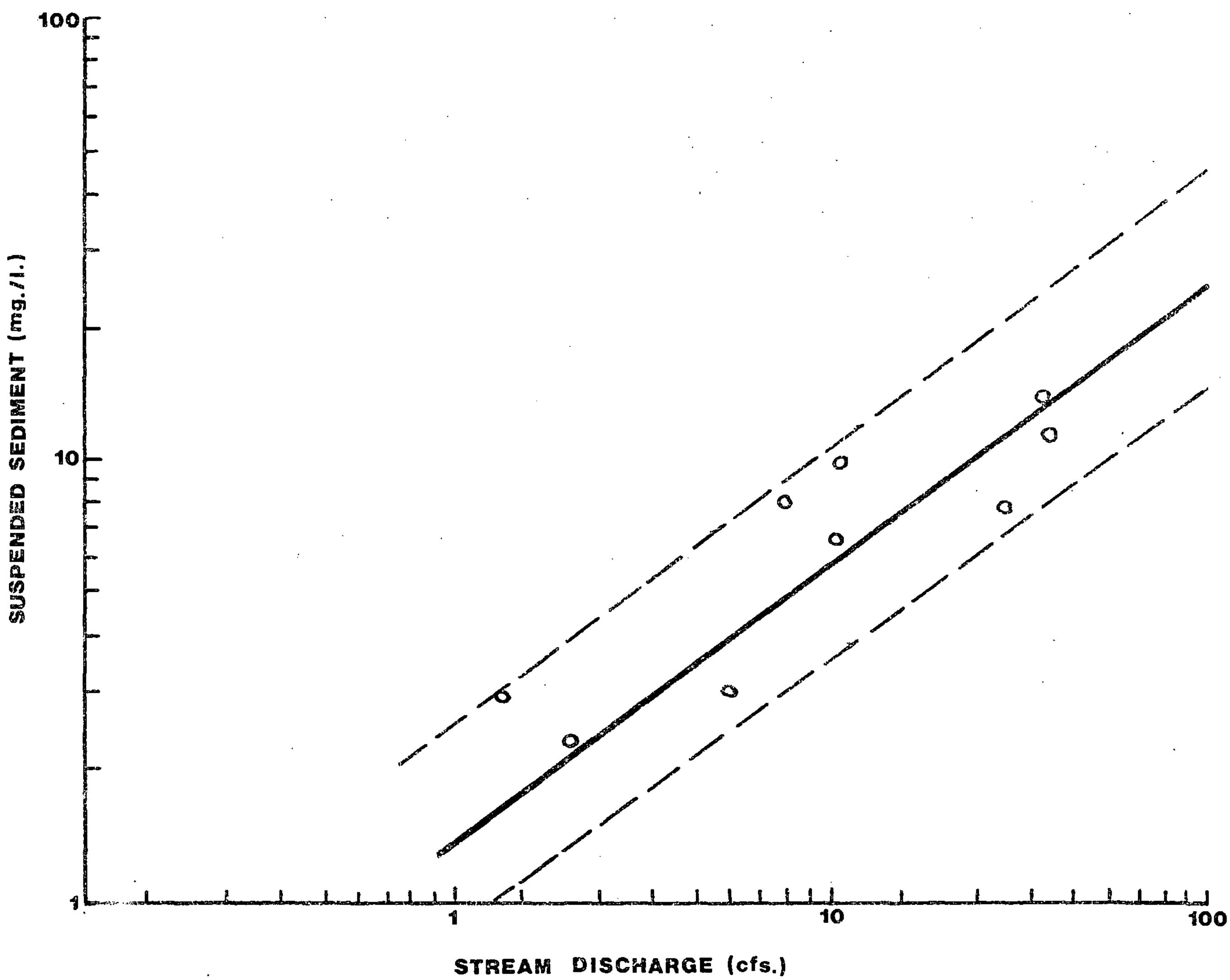


Figure 33.--Sediment rating curve - Pass Creek, 1976. (Rosgen, 1977)

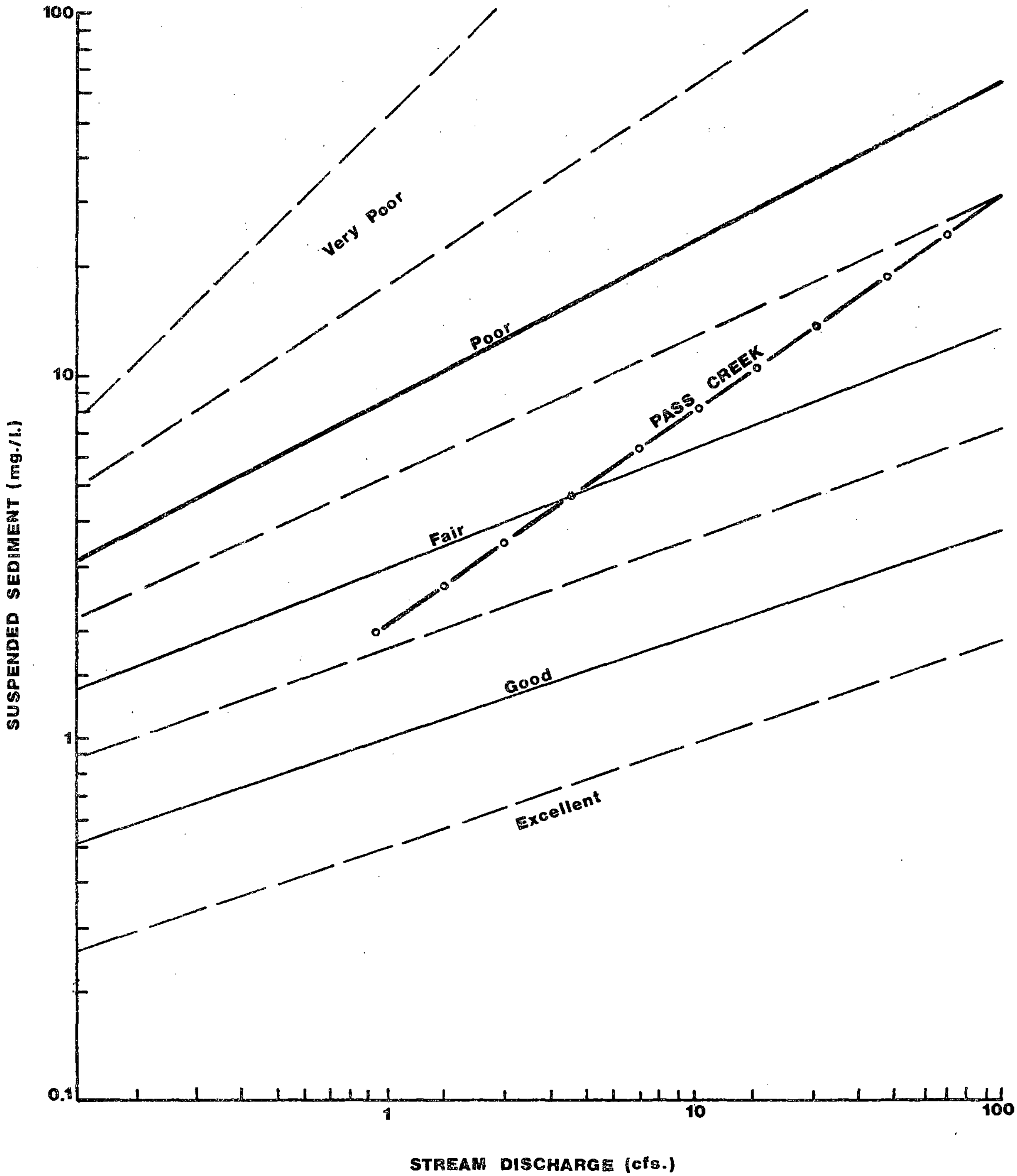


Figure 34.--Sediment rating curve vs. channel stability. (Rosgen, 1977)

Step 12:

> Compare total streamflow increase to confidence bands of either the sediment rating curve or channel stability - rating curve (Figure 33). Determine if exceeding threshold limits.

Introduced Sediment

The analysis procedures presented in this chapter will enable the hydrologist to determine the hydrologic impacts from mining as well as resultant impacts on channel processes. The procedures do not consider introduced sediment. The principles discussed in Chapter 2 must be applied to solve this problem, using an appropriate delivery ratio, and recognizing that sediment introduced from upland sources will diminish with time.

One approach for determining whether or not introduced sediment will cause unacceptable environmental impacts is to use relationships as given in Figure 33. However, rather than using unit discharge and concentration, similar curves can be developed for annual runoff (acre-feet, inches, etc.) and sediment yield (tons per year, etc.). It can be assumed that the introduction of quantities of sediment which exceed the upper confidence limits at a given discharge will cause channel readjustments. Accordingly, quantities of introduced sediment (computed using the guidelines presented in Chapter 2) that exceed the upper confidence band for a given discharge largely reflect the extent of impact on the channel system from on-site erosion. Such impacts are more easily detected in stable channels that have narrow confidence bands. Wider confidence intervals, normally associated with the less stable channels, will require greater quantities of introduced sediment to show adverse impacts from mining activities.

CONCLUSIONS

Although the analysis procedures presented in this chapter are by no means a comprehensive treatment of specific non-point source problems associated with mining activities, they do illustrate application of the more important concepts presented in these guidelines. If carefully applied, they will provide a realistic process-oriented quantitative assessment of hydrologic impacts and resultant impacts on channel processes.

Guidelines for handling introduced sediment are presented in Chapter 2. These procedures should be considered preliminary and subject to revision as additional field data become available.

CHAPTER 8

PHASE II - FIELD VERIFICATION

Any engineering system for quantifying non-point source pollution must be formulated using a considerable amount of empiricism. Accordingly, field calibration is extremely important in order to build confidence in its use. This is particularly the case in the introduced sediment portion portion of these guidelines (Chapter 2). Few data are available on most aspects of the problem of surface erosion and delivery. Accordingly, a field program (Phase II) is proposed in order to pilot-test the procedures proposed in Chapter 2. Such studies should include: (1) detailed hydrologic analyses of selected watersheds; (2) applications of modified USLE, based on these analyses; (3) channel stability and suspended sediment rating curve analyses; and (4) evaluations of baseline sediment yields (ε_η) for delivery ratio determinations. Simultaneous studies should be made on watersheds disturbed and undisturbed by mining activities, and should continue for a period of at least 2 years.

CHAPTER 9

PRINCIPLES OF EROSION AND SEDIMENT YIELD FROM SAGEBRUSH LANDS

Assessments of hydrologic impacts from mining activities in sagebrush lands can be made using the same procedures discussed in these guidelines. However, a hydrologic analysis unique to this vegetation type must be used to quantify changes in the water cycle.

A computerized simulation model has recently been developed by the Rocky Mountain Forest and Range Experiment Station (Haeffner et al., 1974). This model is a version of the Subalpine Water Balance model, but modified to account for growth, water use, energy balance, and snowpack characteristic of the sagebrush vegetation type.

Additional research is needed in order to develop regionalized techniques for quantifying hydrologic impacts similar to those proposed in these guidelines for the subalpine zone. These studies would involve calibrating the model to representative watersheds and generating response data similar to that presented in Chapter 4.

The guidelines for quantifying erosion and channel processes in subalpine environments appear also to be applicable to the sagebrush type. However, these procedures have not been applied on the ground to any great extent. Accordingly, at the very least, short-term pilot studies should be initiated to validate the methodology once it has been developed.

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APPENDIX I

WATER SOIL LOSS EQUATION (USLE) COMPUTATIONAL PROCEDURES

(Excerpted from Utah Water Research Laboratory, 1976)

APPENDIX C

EXAMPLES OF WATER EROSION CALCULATIONS

EXAMPLE NO. 1

Six general highway cross-sections are identified by number in Figure C-1. These, or slight variations of them, may be considered as erosion source area configurations during the construction of any highway. The example that follows will refer to cross-section number 1, but the same procedures would apply to any of the other five. The geographical area selected for use in the example is the northwestern corner of Missouri, on a soil with a K value of 0.30. The example is purely hypothetical and is presented solely to illustrate calculation procedures. It assumes that all highway engineering structures such as ditches, downdrains, energy dissipators, etc., are adequately designed and function properly.

This example will illustrate the procedure for obtaining appropriate VM factors and weighting them over time (scheduling) and space (two or more controls in the same segment) to obtain average VM factors for the entire segment. It assumes that soil K values

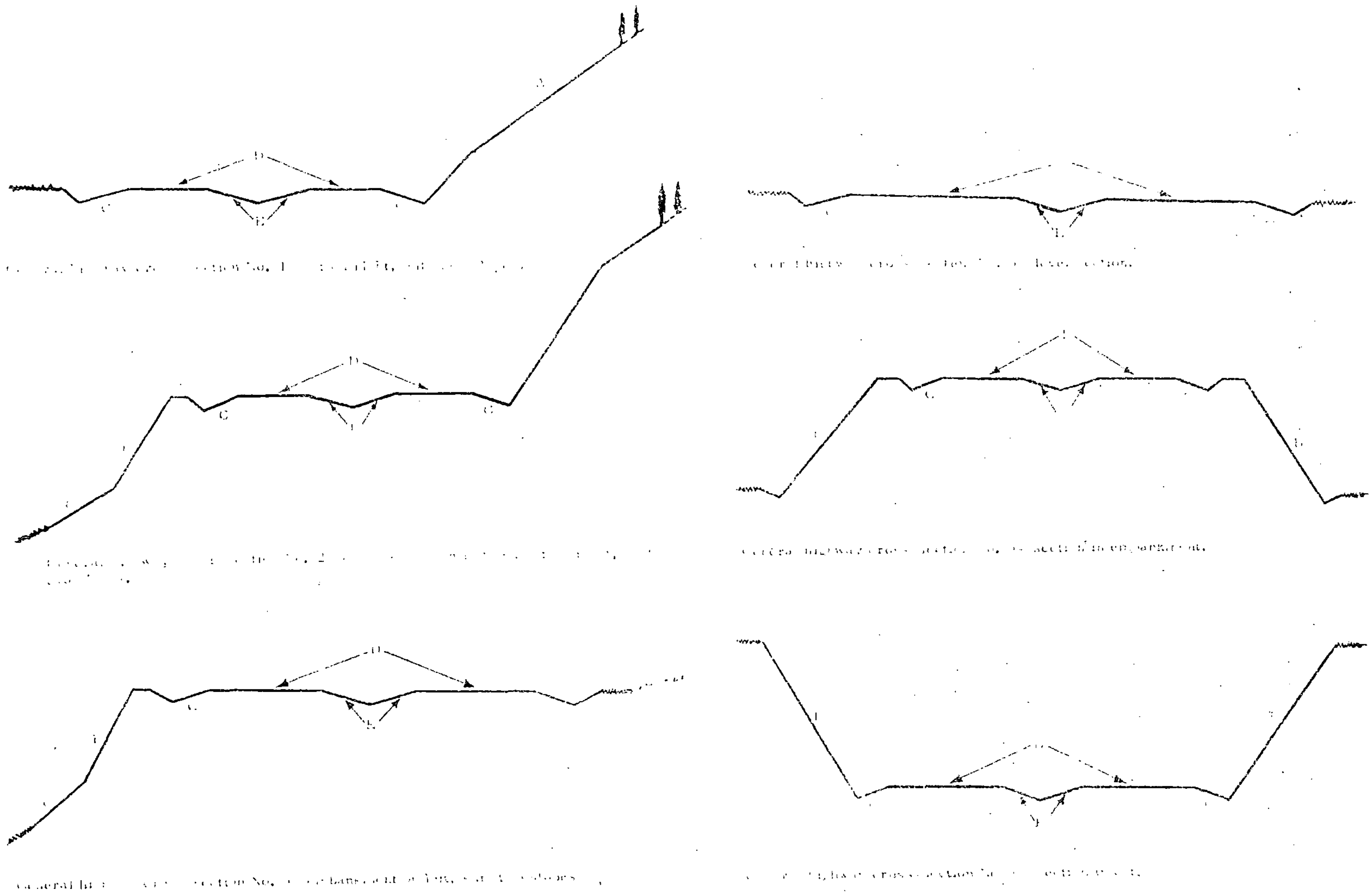


Figure C-1. General highway cross-sections.

are the same for all cross-section segments. The rainfall factor, R, is chosen as 165 on an average annual basis. The construction period is selected as 12 months.

The basic conditions for this cross-section (see Figure C-1, No. 1) are tabulated below.

Segment	R-value	K-value	Segment length, ft.	Slope %
Upper Slope (A)	165	0.30	100	20
Cut Slope (B)	165	0.30	40	33
Outside Shoulder (C)	165	0.30	25	10
Roadbed (D)	165	0.30	350[1]	3
Median (E)	165	0.30	40[2]	8

[1] Average distance between roadbed cross drains; roadbed width is 70 feet for each direction, 140 feet total.

[2] Each half of the median is 40 feet wide, total width is 80 feet.

A AND B SEGMENTS

Since the example assumes that no ditch separates the A and B segments, they can be considered jointly.

LS Value

The LS value for segments A and B (an irregular slope) is calculated as a joint value (31, 98, and personal communication).

$$LS = \frac{\sum_{j=1}^{n} \left(\left[S_j(\lambda_j^{1.6}) - S_j(\lambda_{j-1}^{1.6}) \right] \left[\frac{10000}{10000 + s^2} \right] \right)}{\lambda_e (72.6^{0.6})} \quad \text{. . . . .} \quad (C-1)$$

in which

S_j = Wischmeier's Factor S for the j^{th} slope segment

$$\text{Factor } S = \frac{0.43 + 0.3s + 0.043s^2}{6.613} \quad \text{. . .} \quad (C-2)$$

s = percent slope

λ_j = total slope length from the bottom of the j^{th} segment to the top of the slope, ft.

λ_{j-1} = total slope length above the j^{th} segment, ft.

λ_e = overall slope length, ft.

In the present case, from Eq. C-2

$S_{20} = 3.57,\ S_{33} = 8.64$

and from Eq. C-1

$$LS = \frac{\left[\left(3.57(100^{1.6}) - 0\right) + \left(8.64(140^{1.6}) - 8.64(100^{1.6})\right) \right] \left[\frac{10000}{10000 + s^2} \right]}{140(72.6^{0.6})}$$

LS = 7.78

<u>Erosion Potential, A_1</u>

The erosion potential (A_1) for the A and B segment,

A_1 = RKLS = 165(0.30)(7.78) = 385 tons/ac./yr.

$\frac{385}{43,560}$ x 140 = 1.24 tons/ft. width of slope per year

Site and Operations

Total slope length is 140 feet up to a stand of native hardwoods and brush. No runoff is expected from this area. Both slopes were completely bared during the construction period. The time from grubbing and clearing to final shaping was three months. The bare soil condition at the end of final shaping is described as bulldozer compacted, scraped across the slope. As soon as final grading was completed the A and B segments were covered with topsoil, and seed and fertilizer were applied. The seeded area was straw mulched--punched into the soil across the slope. No grass growth is expected for four months (late fall seeding), and an established permanent grass cover is expected to take an additional three months (seven months total from date of seeding).

Erosion Control Schedule

1.	Bare soil, no erosion controls	3 months
2.	Straw mulch	4 months
3.	Early grass growth, with mulch	3 months
4.	Established permanent grass	2 months

VM Factors

	Description of Factor	Source of Value	Factor Value
1)	Bare soil, bulldozer compacted scraped across slope	Table 5-2	1.20
2)	Straw mulch, punched in, across slope, 2.5 tons/acre[1]	Figure 5-13 (results from literature)	0.01
3)	Early grass growth with mulch described in number 2	Use mulch value	0.01
4)	Established permanent grass	Table 5-2	0.01

[1] With RKLS equal to 385, Figure 5-13 indicates a minimum design mulching rate of about 2.5 tons/ac. Rates at or in excess of the minimum have values of 0.01.

Factor Weights

Since all erosion control treatments occupy the same area, no area weighting of factors is required.

Time weighting of control treatments is required and is accomplished as follows (10):

Control Source	Months	VM Factor		Fraction of Const. Period		Product
None	3	1.20	x	3/12	=	0.30
Straw mulch, early growth, established grass	9	0.01	x	9/12	=	0.01
					Sum	0.31
						= VM

Expected Soil Loss, A_2

The expected soil loss, A_2,

$$A_2 = A_1 \ VM = 385(0.31) = 119 \text{ tons/ac./yr.}$$

$$\frac{119}{43,560} \times 140 = 0.38 \text{ tons/ft. width of slope per year}$$

C SEGMENT

This segment is the outside road shoulder.

LS Value

The LS value for a single, uniform, segment,

$$LS = ((0.43 + 0.3s + 0.043s^2)/6.613) \cdot (L/72.6)^{0.5} \cdot \left(\frac{10000}{10000 + s^2}\right) \quad \ldots\ldots \quad (C-3)$$

in which

s = slope steepness, percent

L = slope length, ft.

In the present case, from Eq. C-3

$$LS = 1.17 \cdot 0.59 \cdot 0.99 = 0.68$$

Erosion Potential, A_1

The erosion potential, A_1, for each portion of the C-Segment,

$$A_1 = RKLS = 165(0.30)(0.68) = 33.7 \text{ tons/ac./yr.}$$

$$\frac{33.7}{43,560} \times 25(2) = 0.04 \text{ tons/yr/ft width of outside shoulders}$$

Site and Operations

The outside road shoulders were not treated for erosion control until the roadbed was at final grade, seven months after the area was grubbed and cleared. During this seven-month period the bare soil is described as rough and irregular, tracked all directions. At the end of 7 months the outside shoulders were treated for erosion control. Starting at the top of the shoulder the treatments are: (1) a 3-foot strip of gravel, (2) a 2-foot strip of grass sod, (3) a 16-foot strip of grass seed, fertilizer and blown straw, and (4) a 4-foot strip treated the same as (3), and with an excelsior mulch blanket held within plastic netting and pinned down with wire staples. Grass growth is expected within 10 days; established grass stands are expected to take four months.

Erosion Control Schedule

1.	Bare soil, no erosion control	7 months
2.	Gravel, sod, seed, fertilizer, straw, excelsior blanket	5 months

VM Factors

	Description of Factor	Source of Value	Value
1)	Bare soil, rough and irregular, tracked all directions	Table 5-2	0.90
2)	Gravel mulch, 140 tons/ac.	Figure 5-15 (results from literature)	0.01
3)	Grass sod (permanent seeding)	Table 5-2	0.01
4)	Straw mulch, blown on, not anchored, 1.0 ton/ac.	Figure 5-12 (results from literature)	0.20
5)	Early grass growth, 4 months growth	Table 5-2	0.05
6)	Established permanent grass	Table 5-2	0.01
7)	Same as number 4 with excelsior blanket	Table 5-2	0.04

Number 2, gravel mulch at a rate of 140 tons/ac., is the minimum design rate from Figure 5-15.

Number 4, straw mulch, not anchored, at 1 ton/ac. is slightly underdesigned; the minimum design rate is 1.25 tons/ac. When use

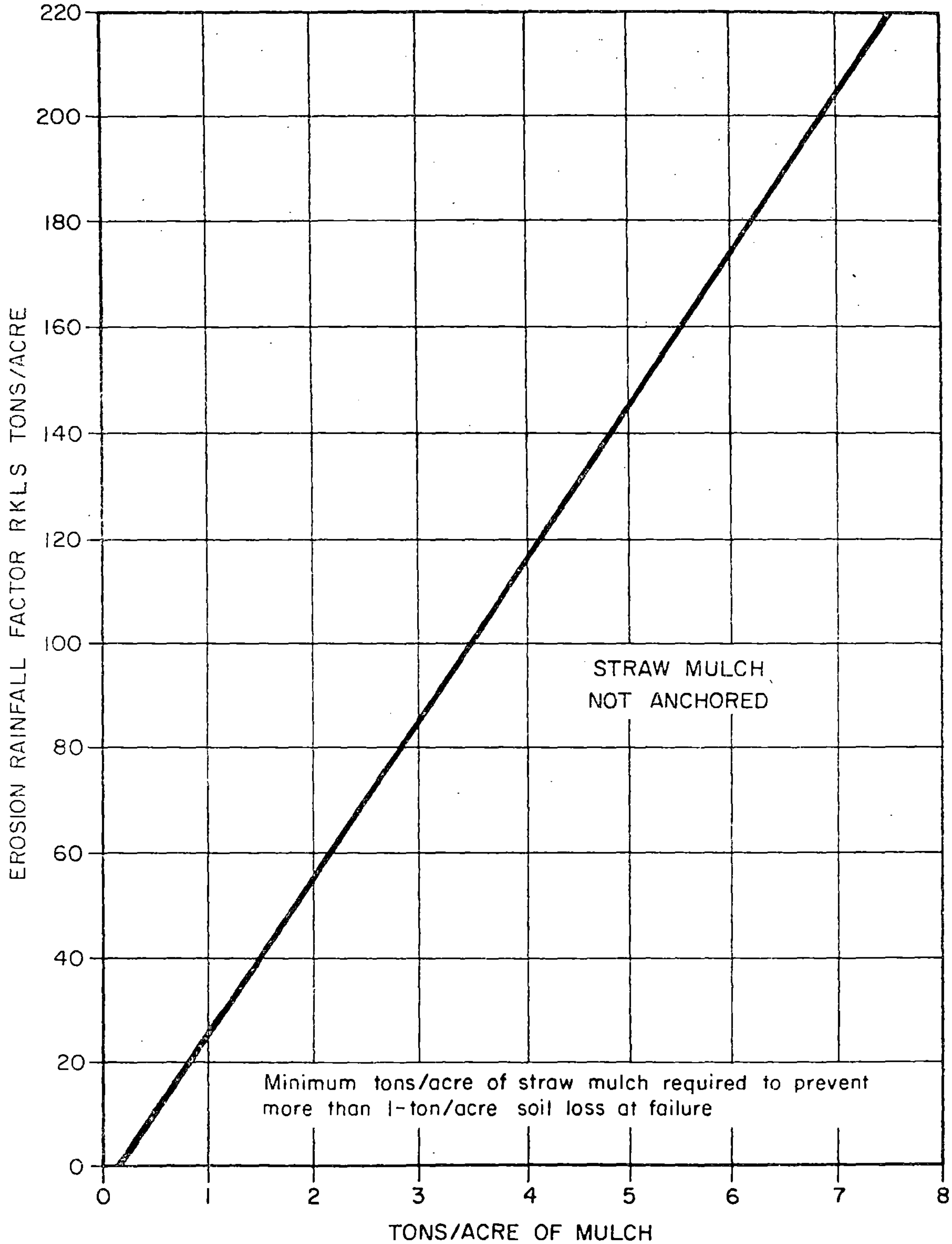


Figure 5-12. Straw mulch not anchored vs. RKLS.

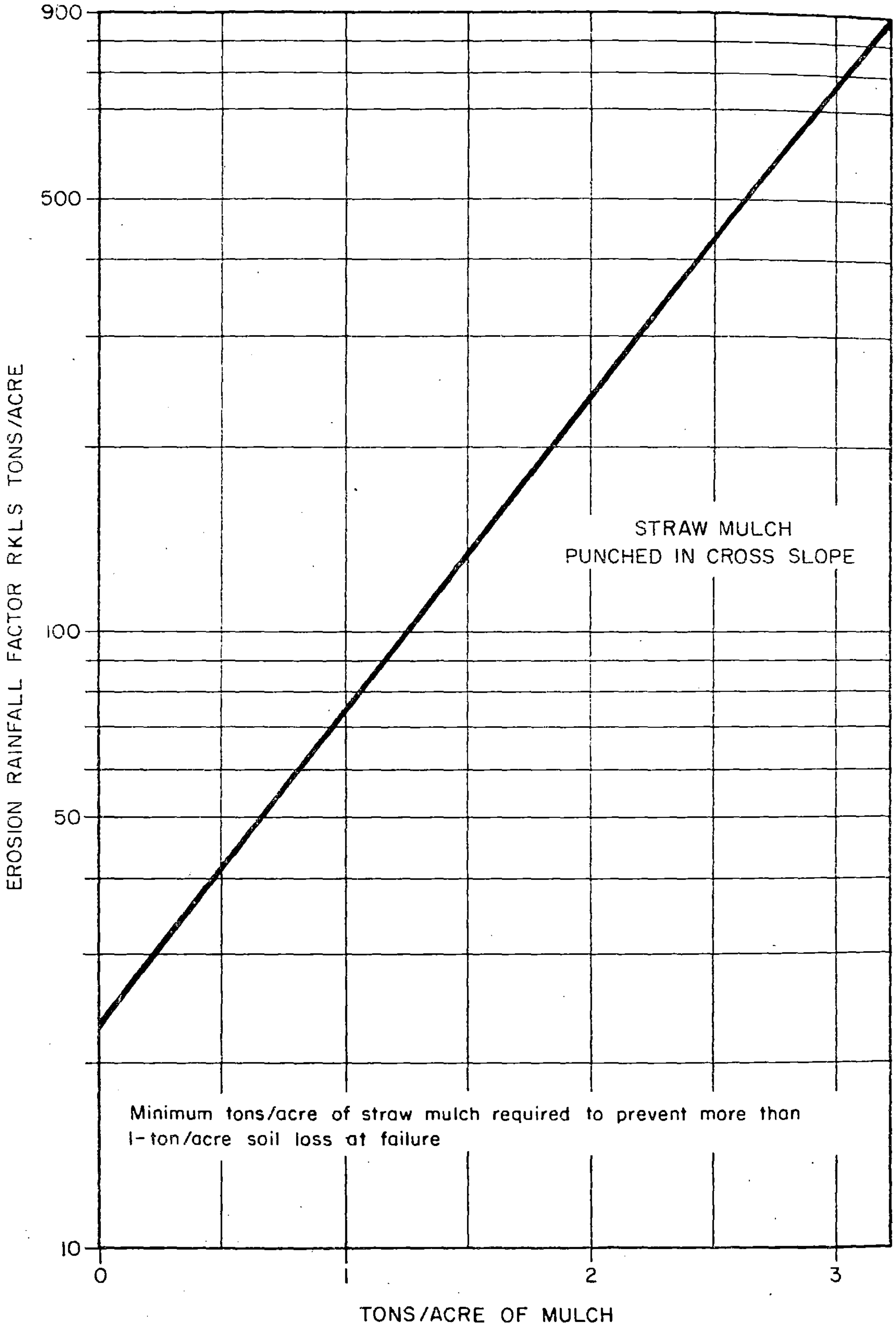


Figure 5-13. Straw mulch anchored vs. RKLS.

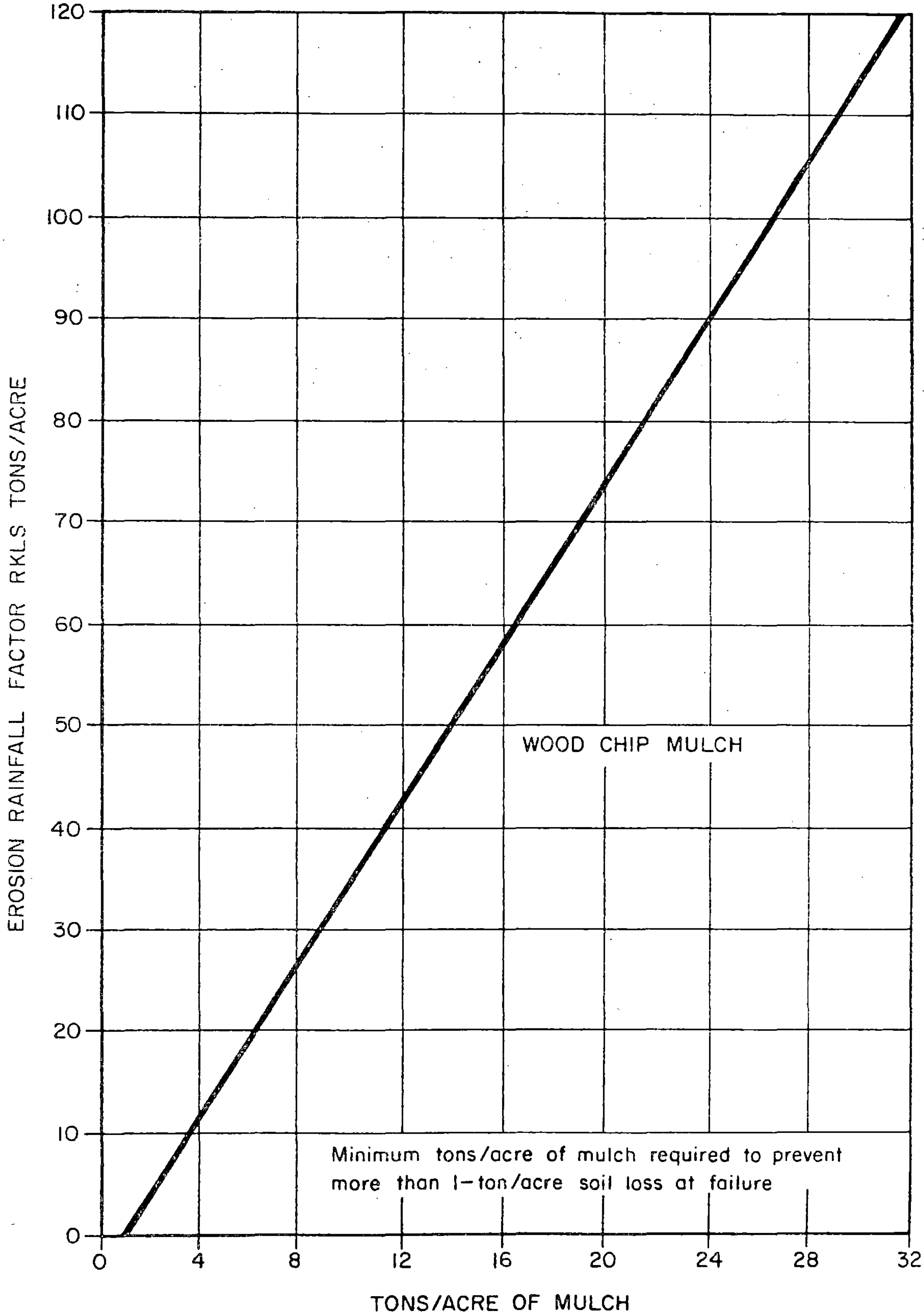


Figure 5-14. Wood chip mulch vs. RKLS.

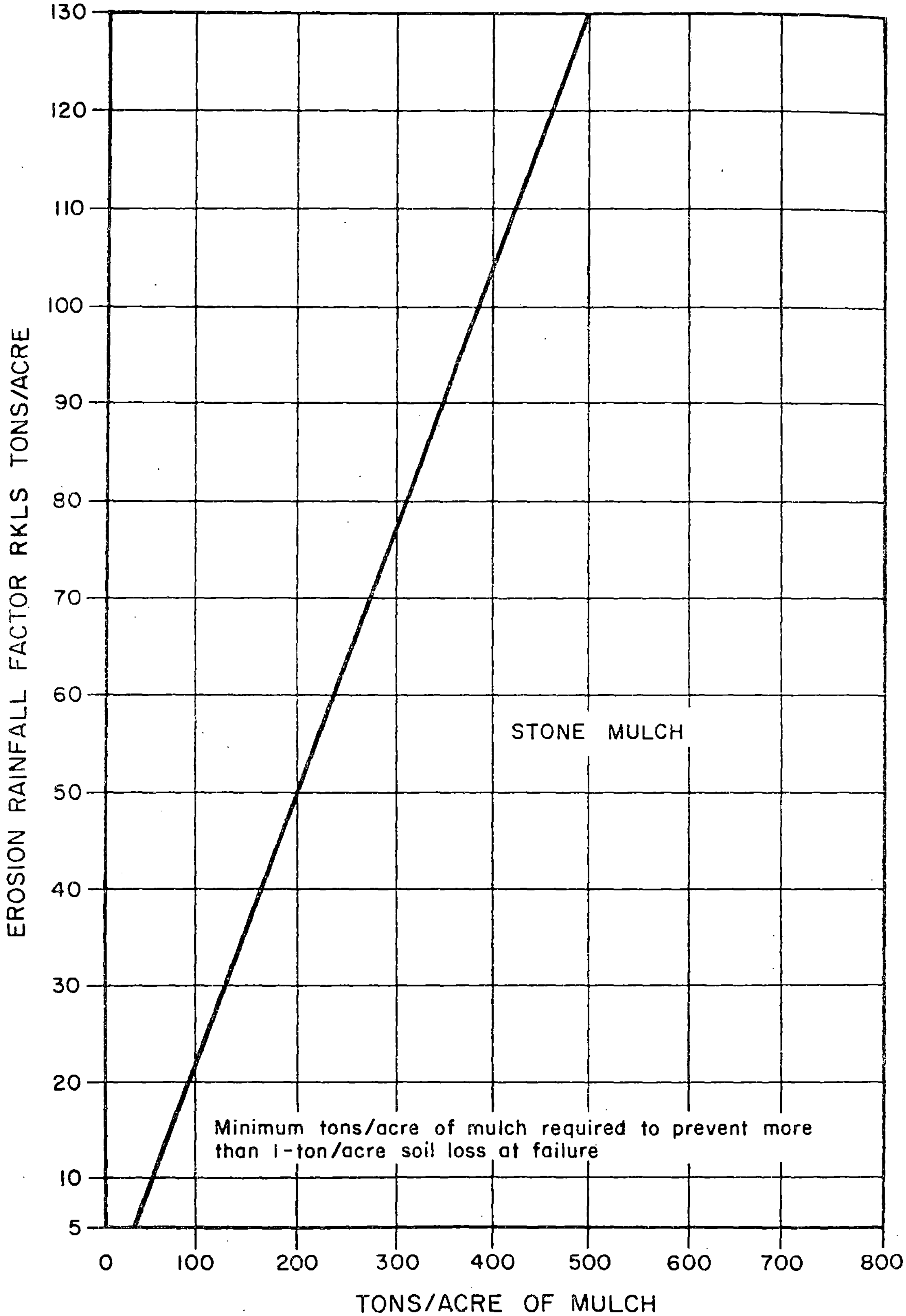


Figure 5-15. Stone mulch vs. RKLS.

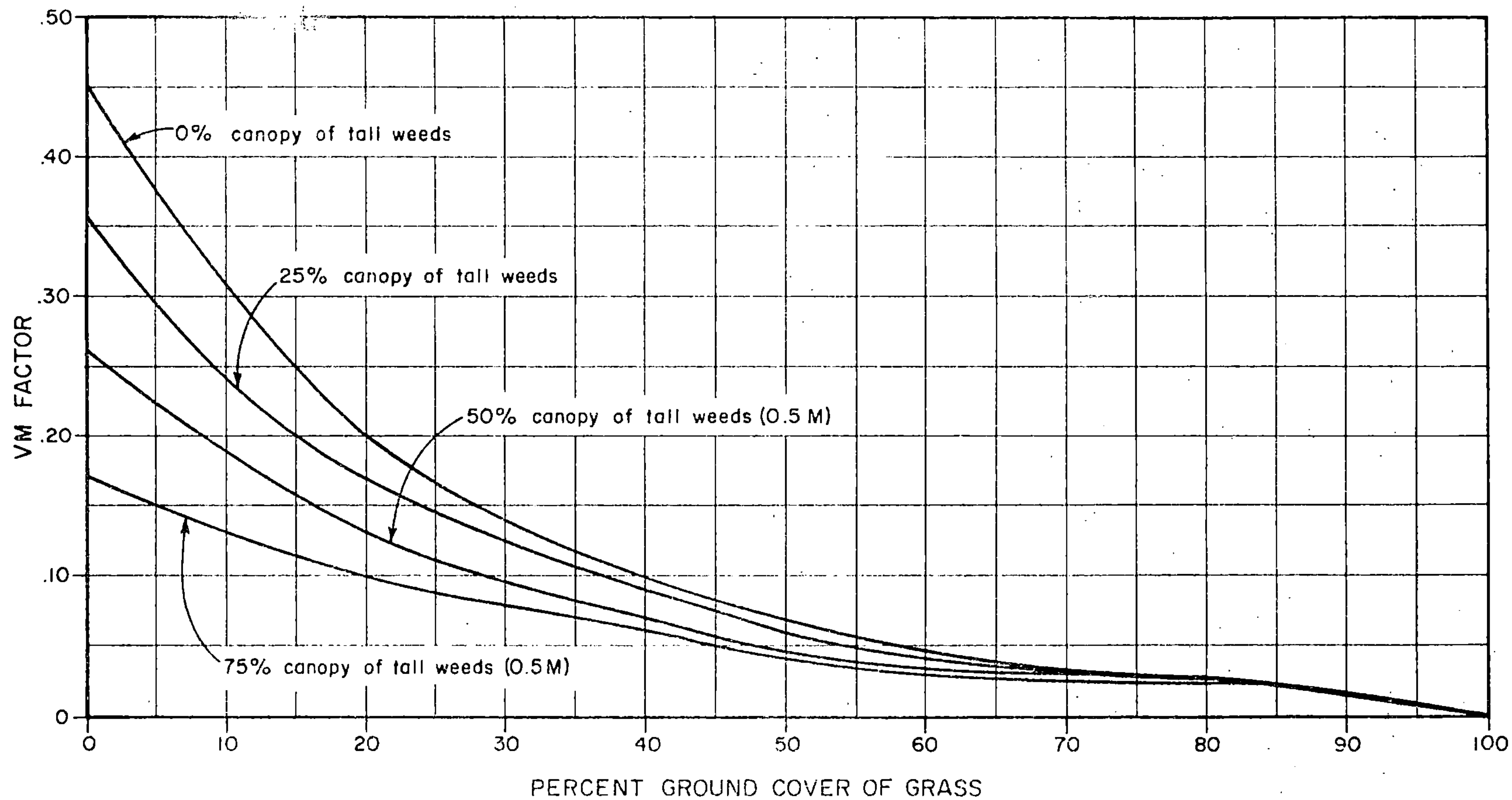


Figure 5-16. Relationship between grass density and VM factor.

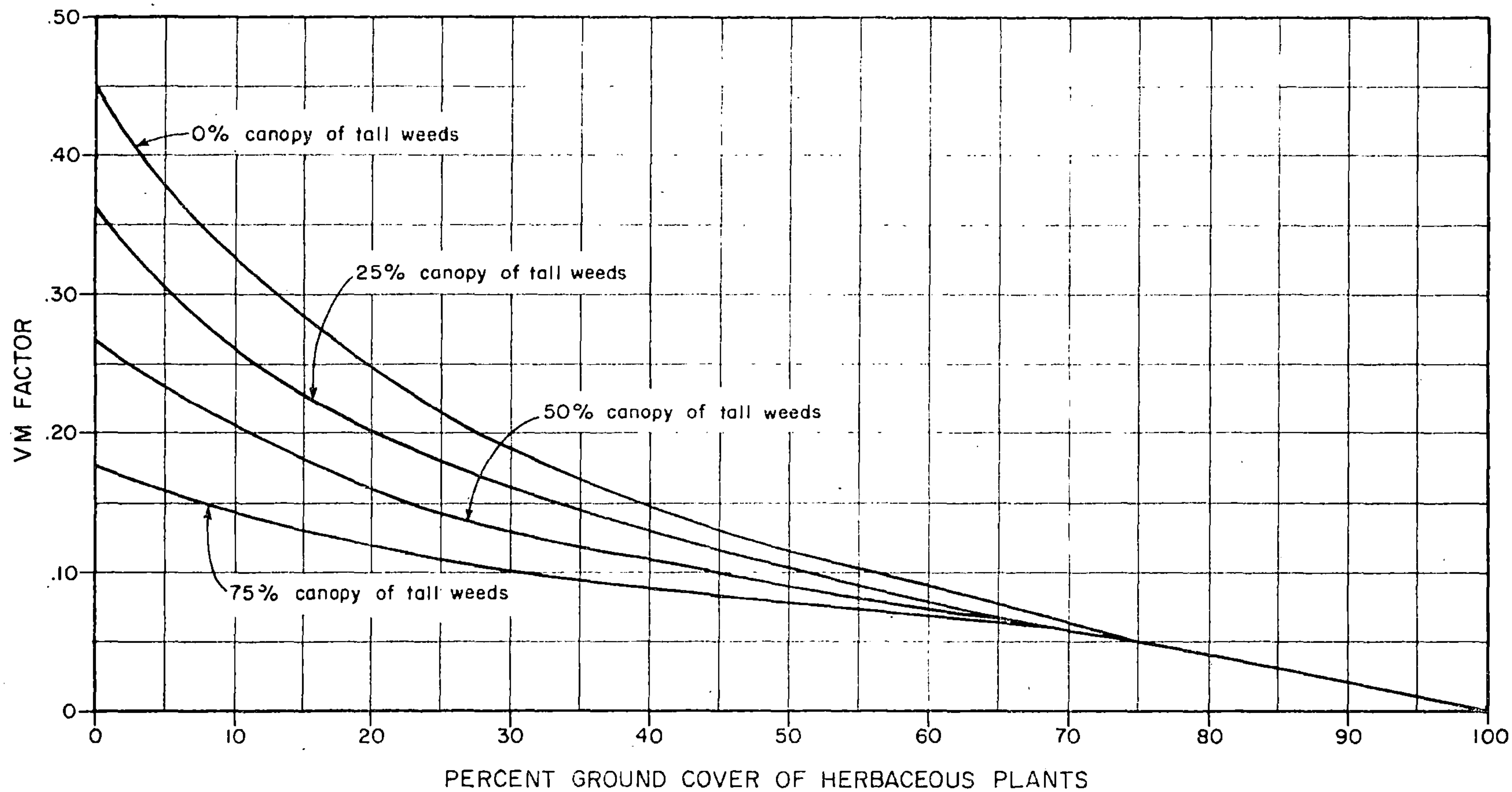


Figure 5-17. Relationship between forb density and VM factor.

Table 5-2. Typical VM factor values reported in the literature.*

Condition	VM factor
1. Bare soil conditions	
freshly disked to 6-8 inches	1.00
after one rain	0.89
loose to 12 inches smooth	0.90
loose to 12 inches rough	0.80
compacted bulldozer scraped up and down	1.30
same except root raked	1.20
compacted bulldozer scraped across slope	1.20
same except root raked across	0.90
rough irregular tracked all directions	0.90
seed and fertilize, fresh	0.64
same after six months	0.54
seed, fertilize, and 12 months chemical	0.38
not tilled algae crusted	0.01
tilled algae crusted	0.02
compacted fill	1.24-1.71
undisturbed except scraped	0.66-1.30
scarified only	0.76-1.31
sawdust 2 inches deep, disked in	0.61
2. Asphalt emulsion	
1250 gallons/acre	0.02
1210 gallons/acre	0.01-0.019
605 gallons/acre	0.14-0.57
302 gallons/acre	0.28-0.60
151 gallons/acre	0.65-0.70
3. Dust binder	
605 gallons/acre	1.05
1210 gallons/acre	0.29-0.78
4. Other chemicals	
1000 lb fiber Glass Roving with 60-150 gallons/acre	0.01-0.05
Aquatain	0.68
Aerospray 70, 10 percent cover	0.94
Curasol AE	0.30-0.48

Table 5-2. Continued.

Condition	VM factor
4. Other chemicals (continued)	
Petroset SB	0.40-0.66
PVA	0.71-0.90
Terra-Tack	0.66
**Wood fiber slurry, 1000 lb/acre fresh	0.05
**Wood fiber slurry, 1400 lb/acre fresh	0.01-0.02
**Wood fiber slurry, 3500 lb/acre fresh	0.10
5. Seedings	
temporary, 0 to 60 days	0.40
temporary, after 60 days	0.05
permanent, 0 to 60 days	0.40
permanent, 2 to 12 months	0.05
permanent, after 12 months	0.01
6. Brush	0.35
7. Excelsior blanket with plastic net	0.04-0.10

*Note the variation in values of VM factors reported by different researchers for the same measures. References containing details of research which produced these VM values are included in Volume III of the report, "Bibliography of Water and Wind Erosion Control References."

**See mulch curve in Figure 5-12.

rates are less than minimum design rates the VM factor values are undefined. However, as an approximation the following procedure may be used.

$$\left| \frac{X - Y}{Y} \right| \rightarrow \text{VM factor}, \leq 0.33 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (C\text{-}4)$$

in which

X = actual rate of use and $X < Y$

Y = minimum design rate and $Y > X$

straight brackets indicate the absolute value

In the present case,

$$\left| \frac{1 - 1.25}{1.25} \right| = 0.20$$

If the use of Eq. C-4 yields a value greater than 0.33, the method should not be used.

Number 7, the excelsior blanket over straw mulch, has no known VM factor. In this case, we have used the VM factor for the excelsior blanket because it is lower than that of the straw mulch.

Factor Weights

In the preceding section on VM factors, numbers 4 and 5 will occupy the same area. The straw mulch has a constant value of 0.20.

Grass growth has a changing VM factor that at the end of four months growth is expected to be 0.05. What is the appropriate VM factor during the four-month period? Since the VM factor changes from 0.2 to 0.05 in four months the average is $(0.2 + 0.05)/2 = .125 \approx 0.13$.

Because this segment is treated with several different erosion control measures area-weighting is required for the four-month period of early grass growth.

Control Source	VM Factor	Area Covered	Product
Gravel mulch	0.01	0.12	0.001
Grass sod	0.01	0.08	0.001
Grass seed, fertilizer, blown straw	0.13	0.64	0.083
Excelsior blanket	0.04	0.16	0.006
		Sum	0.091
			≈ 0.09

Time weighting of VM factors is as follows.

Control Source	Months	VM Factor		Fraction of Const. Period		Product
None	7	0.90	x	7/12	=	0.53
Gravel, sod, seed, fertilizer straw, excelsior	4	0.09	x	4/12	=	0.03
Gravel, sod, permanent grass	1	0.01	x	1/12	=	0
				Sum		0.56
						= VM

Expected Soil Loss, A_2

The expected soil loss, A_2

$A_2 = A_1 \ VM = 33.7(0.56) = 18.9$ tons/ac./yr.

$\frac{18.9}{43,560} \times 25(2) = 0.02$ tons/ft. width of shoulders cross-section per year

D SEGMENT

This segment consists of the two roadbeds. The roadbed erosion, unlike the erosion on the other segments of the cross-section, is calculated along the length of the roadbed, i.e., normal to the cross-section. No erosion control measures were used. Therefore, for both roadbeds, the potential soil loss equals the expected soil loss, $A_1 = A_2$.

LS Value

The LS value is calculated from Eq. C-3

$S = 3\%$; $L = 350'$

$LS = 0.57$

Erosion Potential, A_1

$A_1 = RKLS = 165(0.30)(0.57) = 28.2$ tons/ac./yr.

$\frac{28.2}{43,560} \times 140 = 0.09$ tons/ft. width of roadbed cross-section per year

Expected Soil Loss, A_2

$$A_2 = A_1 \ VM = 28.2(1) = 28.2 \text{ tons/ac./yr.}$$

$$\frac{28.2}{43{,}560} \times 140 = 0.09 \text{ tons/ft. width of roadbed cross-section per year}$$

E SEGMENT

This is the median strip.

LS Value

The LS value is calculated from Eq. C-3

$$LS = 0.62.$$

Erosion Potential, A_1

$$A_1 = RKLS = 165(0.30)(0.62) = 30.7 \text{ tons/ac./yr.}$$

$$\frac{30.7}{43{,}560} \times 40(2) = 0.06 \text{ tons/ft. width of median cross-section per year}$$

Site and Operations

The median was not treated for erosion control until the roadbed was at final grade, seven months after the area was grubbed and cleared. The bare soil condition is described as rough and irregular, tracked all directions. At the end of seven months the median was treated for erosion control. Starting at the top, each half of the

median received the following: (1) a 3-foot strip of gravel, (2) a 2-foot strip of grass sod, (3) a 31-foot strip of grass seed, fertilizer, and blown straw, and (4) a 4-foot strip treated the same as (3) and with an excelsior mulch blanket held within plastic netting and pinned down with wire staples. Grass growth is expected within 10 days; established grass stands are expected to take four months.

Erosion Control Schedule

1.	Bare soil, no erosion controls	7 months
2.	Gravel, sod, seed, fertilizer, straw, excelsior blanket	5 months

VM Factors

	Description of Factor	Source of Value	Value
1)	Bare soil, rough and irregular, tracked all directions	Table 5-2	0.90
2)	Gravel mulch, 140 tons/ac.	Figure 5-15 (results from literature)	0.01
3)	Grass sod	Table 5-2	0.01
4)	Straw mulch, blown on, not anchored, 1 ton/ac.	Figure 5-12 (and Equation C-4)	0.13
5)	Early grass growth, 4 months growth	Table 5-2	0.05
6)	Established permanent grass	Table 5-2	0.01
7)	Same as number 4, with excelsior blanket	Table 5-2	0.04

Number 2, gravel mulch, is slightly above the design minimum of 130 tons/acre, Figure 5-15.

Number 4 is slightly less than the design minimum of 1.15 tons/acre, Figure 5-12. Eq. C-4 was used to calculate the value of 0.13 for the VM factor.

Factor Weights

Similar to the C-segment, the straw mulch has a constant value of 0.13. However, early grass growth reduces the VM factor on this portion of the area down to 0.05 over a four-month period. The average value for a four-month period is $(0.13 + 0.05)/2 = 0.09$. Area weighted values,

Control Source	VM Factor	Area Covered	Product
Gravel mulch	0.01	0.075	0.001
Grass sod	0.01	0.05	0.001
Grass seed, fertilizer, blown straw	0.09	0.775	0.070
Excelsior blanket	0.04	0.10	0.004
		Sum	0.076
			≈ 0.08

Time weighting,

Control Source	Months	VM Factor		Fraction of Const. Period		Product
None	7	0.90	x	7/12	=	0.53
Gravel, sod, fertilizer, seed, straw, excelsior	4	0.08	x	4/12	=	0.03
Gravel, sod, permanent grass	1	0.01	x	1/12	=	0
				Sum		0.56
					=	VM

Expected Soil Loss, A_2

$$A_2 = A_1 \ VM = 30.7(0.56) = 17.2 \text{ tons/ac./yr.}$$

$$\frac{17.2}{43,560} \times 40(2) = 0.03 \text{ tons/ft. width of median cross-section per year}$$

SUMMARY

The erosion potentials and expected soil loss for each segment of the cross-section:

Segment	A_1 Erosion Potential tons/ft. width of cross-section per year	A_2 Expected Soil Loss tons/ft. width of cross-section per year
AB	1.24	0.38
C	0.04	0.02
D	0.09	0.09
E	0.06	0.03
	1.43	0.52

Since the sums, 1.43 and 0.52, are both expressed in tons/foot width of cross-section/year, it is a simple matter to determine potential and expected soil losses per acre of right-of-way. The calculations are as follows:

Total width of right-of-way = summation of lengths of individual segments = 100 + 40 + 25+25 + 70+70 + 40+40 = 410 ft.

$$\frac{43,560 \text{ ft}^2}{\text{acre } 410 \text{ ft}} = 106.2 \text{ ft/acre} = \text{length of right-of-way per acre}$$

Potential erosion loss = 106.2 ft/acre x 1.43 tons/ft = 151.9 tons/acre of ROW

Expected erosion loss = 106.2 ft/acre x 0.52 tons/ft = 55.2 tons/acre of ROW

Note: These amounts pertain to a specific ROW (cross-section No. 1, Figure C-1) and not generally to all highway cross-sections.

PERFORMANCE EVALUATION

Performance evaluation in terms of percent effectiveness of erosion control measures is defined as,

$$PE = \frac{(RKLS - RKLSVM)}{RKLS} \times 100$$

$$= \frac{151.9 - 55.2}{151.9} \times 100 = 63.7\%$$

This means that the erosion control system described above is expected to be about 64 percent effective in controlling the potential erosion of this particular site. In other words, the system will stop 64 percent of the erosion that would have occurred had no controls been used.

APPENDIX E

COMPUTATIONAL PROCEDURES FOR TOPOGRAPHIC FACTOR (LS) AND EROSION CONTROL FACTOR (VM)

TOPOGRAPHIC FACTOR LS

Single Slopes

The slope length and slope steepness factors were developed independently, but it is convenient to consider them as a single unit in the soil loss equation. In the original equation (43, 53) the influences of slopes steeper than 20 percent were unproven. Before extending Wischmeier's curves to the steepnesses encountered in highway construction, field plot-data for a number of steep slopes were obtained and data points from them were placed on projections of the slope steepness curve. It was found that the equation (43)

$$S = \frac{0.43 + 0.3s + 0.043s^2}{6.613}$$

in which s is slope gradient in percent, expresses the relation between S factor and s reasonably well for curves steeper than the 2:1 slopes which are found on many construction sites.

The slope length factor follows the relationship developed by Wischmeier (50) which is

$$L = \left(\frac{\lambda}{72.6}\right)^m \cos^2 \theta$$

in which

λ = slope length in feet

$$m = \begin{cases} 0.3 \text{ for slope gradients of 0 to 0.5 percent} \\ 0.5 \text{ for slope gradients of 0.5 to 10 percent} \\ 0.6 \text{ for slope gradients greater than 10 percent} \end{cases}$$

θ = the angle the slope forms with horizontal

The sensitivity of LS factors to shortening of slope lengths on a 2.5:1 (40 percent) fill slope can be illustrated with the following example wherein the original total slope length is 1000 feet. Slope segments are created by installing interceptor ditches across the slope.

Number of Segments	LS Factor of Total Slope	Erosion/ft Width of Slope (tons/yr) (Assume RK=1)
1 at 1000 ft.	51.09	1.1729
2 at 500 ft.	33.70	0.7736
3 at 333 ft.	26.41	0.6063
4 at 250 ft.	22.24	0.5106
5 at 200 ft.	19.45	0.4465

<u>Cutting the slope length in half cuts the erosion by approximately one third or to 65 percent of the original amount.</u>

The reader should remember that erosion potentials are in tons per acre per year. Cutting the slope length in half also cuts the area

in half, and total erosion may be indicated by the LS values. The RKLS value is a rate and must be multiplied by an area to determine total erosion amount.

The only manageable parts of the soil loss equation are the topographic factor LS and the erosion control factor VM. The rainfall factor R and the soil erodibility factor K have both been fixed by nature and cannot be altered by man's activities. The steepness and length of many of the slopes in highway construction, however, are determined by man after he considers the physical setting of the construction site and the requirement of the transportation system. It is obvious that flat slopes and short lengths will have less erosion than steep slopes and long lengths, but the amount of erosion expected for various combinations of length and steepness is not so obvious. The LS factor is therefore a numerical representation of the length-steepness combination to be used with the rainfall factor R and the soil erodibility factor K to estimate the total erosion potential for a particular construction slope. Since the slope and length are determined by the highway designer, a knowledge of the LS factor will aid him in choosing proper combinations of slopes and lengths, and determining when to use berms, cross ditches, terraces or other control practices which effectively reduce the LS factor.

For determining the LS factor to use in the soil loss equation, the following relationship was developed by Foster and Wischmeier (31, 48, and personal communication)

$$LS = \left(\frac{0.43 + 0.3s + 0.043s^2}{6.613}\right) \left(\frac{\lambda}{72.6}\right)^m \left(\frac{10,000}{10,000 + s^2}\right)$$

in which LS = topographic factor

λ = slope length in feet

s = slope gradient

m = exponent dependent upon slope gradient

The nomograph in Figure 5-11 has been developed for solving the above equation. For example if the site calls for a fill slope 100 feet long at a steepness of 67 percent ($1\frac{1}{2}$:1) the LS factor value from the nomograph is about 27. Reducing the slope to 50 percent increases the length to 125 feet (increasing the exposed area by 25 percent), and the new LS factor value becomes 20. The erosion rate potential has thus been reduced to 76 percent of the original and the erosion amount to 95 percent (assuming no erosion prior to exposure). Further reducing the slope to 3:1 (33 percent) the LS factor value becomes 13 or 46 percent of the original and total erosion is reduced to 86 percent of the original value. A 6:1 slope would reduce the LS value to about 7 or nearly 24 percent of the first design, but the slope length has now more than tripled to 337 feet and the total amount of erosion has reduced to about 83 percent of the original.

Multiple Slopes

The soil loss equation is based on the assumption that the sediment load carried by the runoff is limited only by the amount of material detached and not by the capacity of the water to carry the detached material. Under this assumption the sediment load increases as the water moves downslope and the runoff from the upper slope adds to the rainfall on the lower slope and thus increases the erosion rate on the lower slope. Where more than one slope is involved it is not sufficient to just average the steepness and use the total length to arrive at an LS factor. To obtain an LS which accounts for the effect of the upper slopes the following method devised by Foster and Wischmeier (31, and personal communication) is recommended.

$$LS = \frac{1}{\lambda_e} \sum_{j=1}^{n} \left[\frac{S_j \lambda_j^{m+1}}{(72.6)^m} - \frac{S_j \lambda_{j-1}^{m+1}}{(72.6)^m} \right] \left[\frac{10000}{10000 + s^2} \right]$$

in which

S_j = slope factor = $\dfrac{0.043\ s^2 + 0.3s + 0.43}{6.613}$ for segment j

λ_j = the length in feet from the top of the slope to the lower end of any segment j

λ_{j-1} = the slope length above segment j

λ_e = overall slope length

m = a coefficient which depends on range of slope steepness

s = slope in percent

or

$$LS = \frac{1}{\lambda_e} \sum_{j=1}^{n} (u_{2j} - u_{1j}) \left(\frac{10000}{10000 + s^2}\right)$$

in which

$$u_{2j} = \frac{S_j \lambda_j^{m+1}}{(72.6)^m}, \quad u_{1j} = \frac{S_j \lambda_{j-1}^{m+1}}{(72.6)^m}$$

Values of u are determined from graphs of $u = S\left(\lambda^{m+1}/(72.6)^m\right)\left(\frac{10,000}{10,000 + s^2}\right)$ (Figures E-1, E-2, and E-3). The procedure for using the graphs is given by Foster and Wischmeier (31) as follows. The graph is entered on a horizontal axis with the value of λ_{j-1}. Moving upward to the curve for the percent slope for segment j, the value of u_{1j} is read on the vertical scale. The graph is then entered with the value of λ_j to obtain the corresponding value of u_{2j}. The difference, $u_{2j} - u_{1j}$, then equals the quantity $(S_j \lambda_j^{m+1} - S_j \lambda_{j-1}^{m+1})/(72.6)^m$.

This procedure is repeated for each of the slope segments, and the n values of $(u_{2j} - u_{1j})$ are summed. Dividing the sum by the overall slope length λ_e gives the effective LS value for the entire length of the irregular slope. The LS value determined by this procedure is a function of all the segment lengths and slope steepnesses and of their particular sequence on the slope.

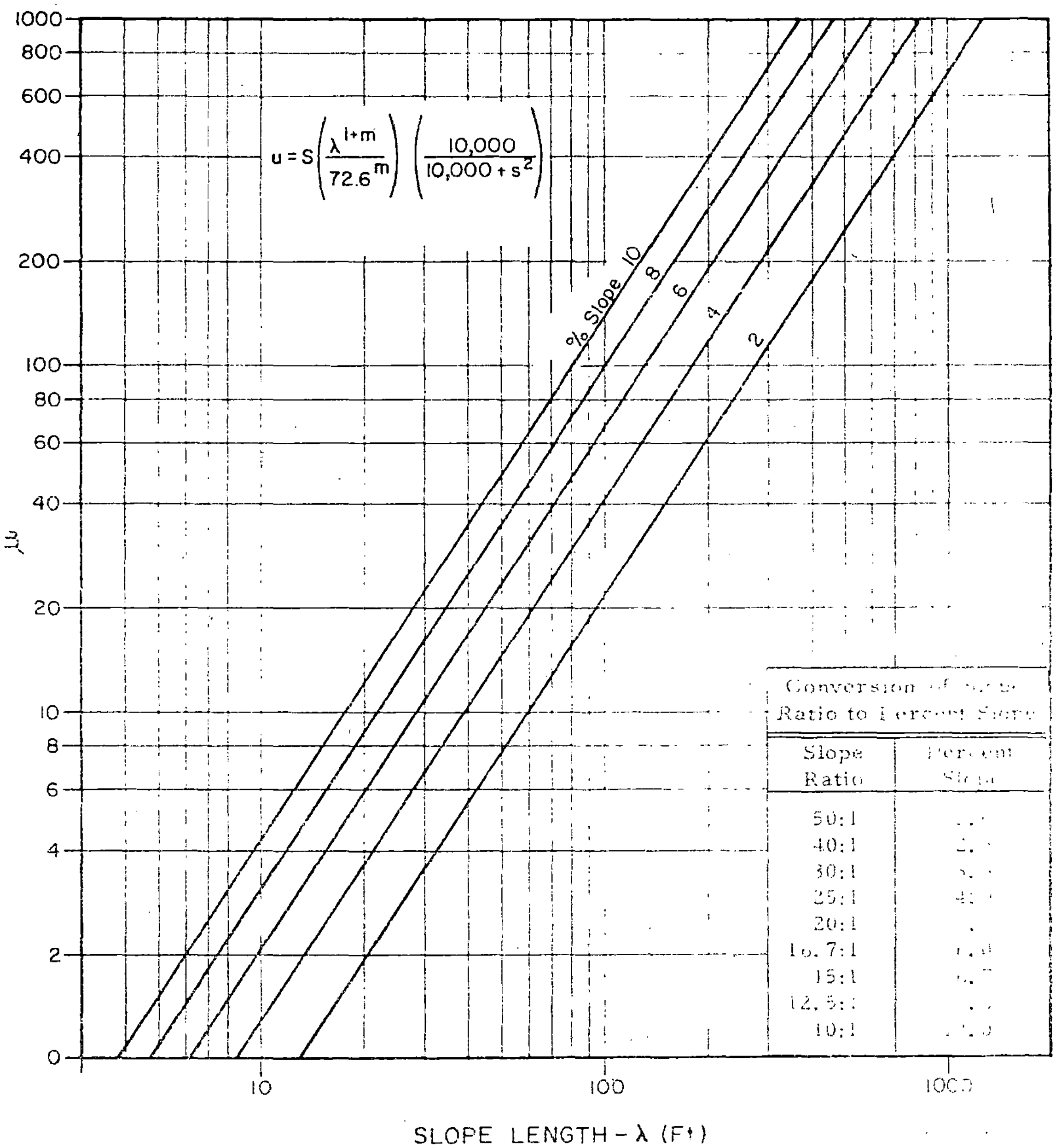
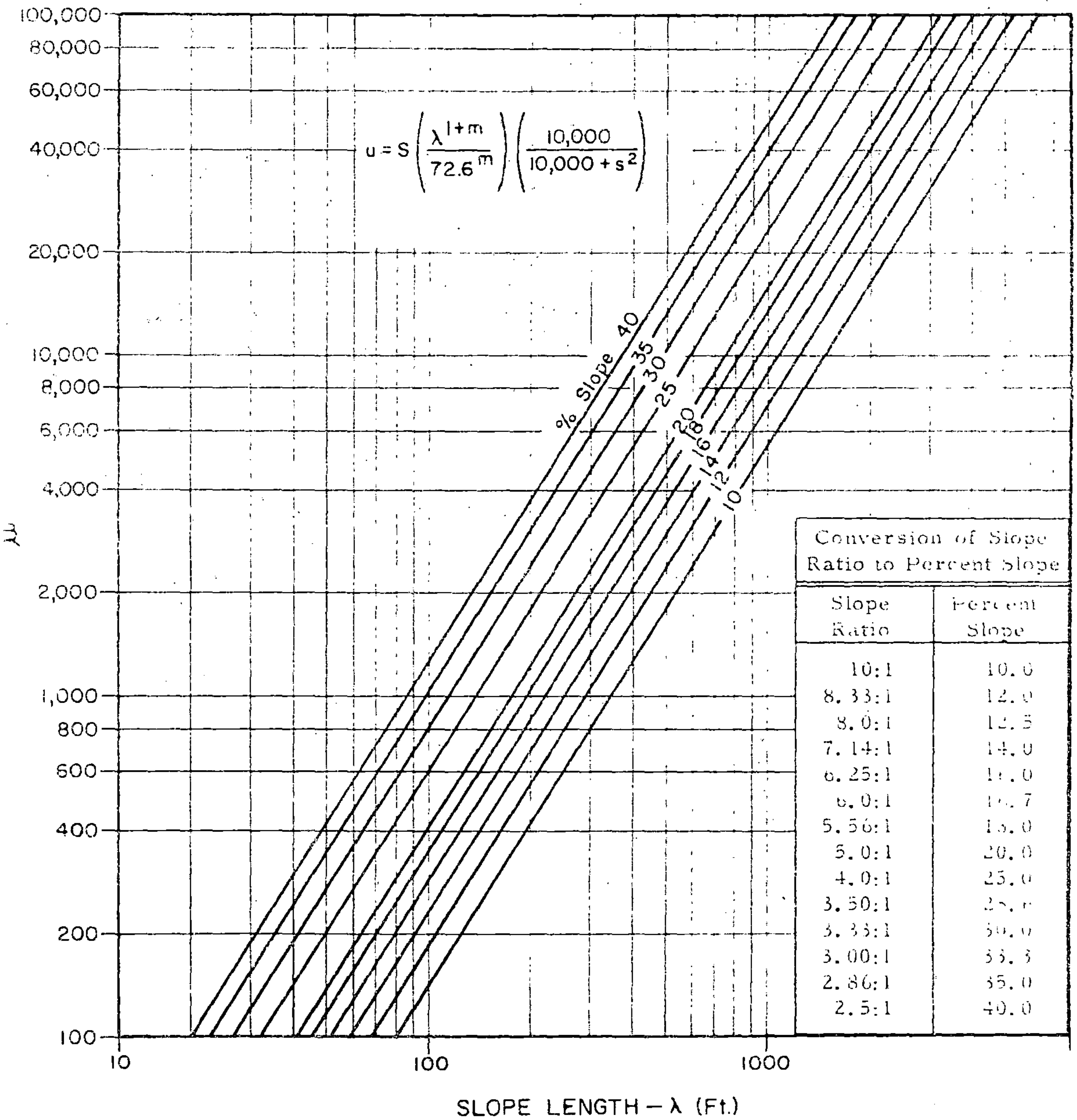
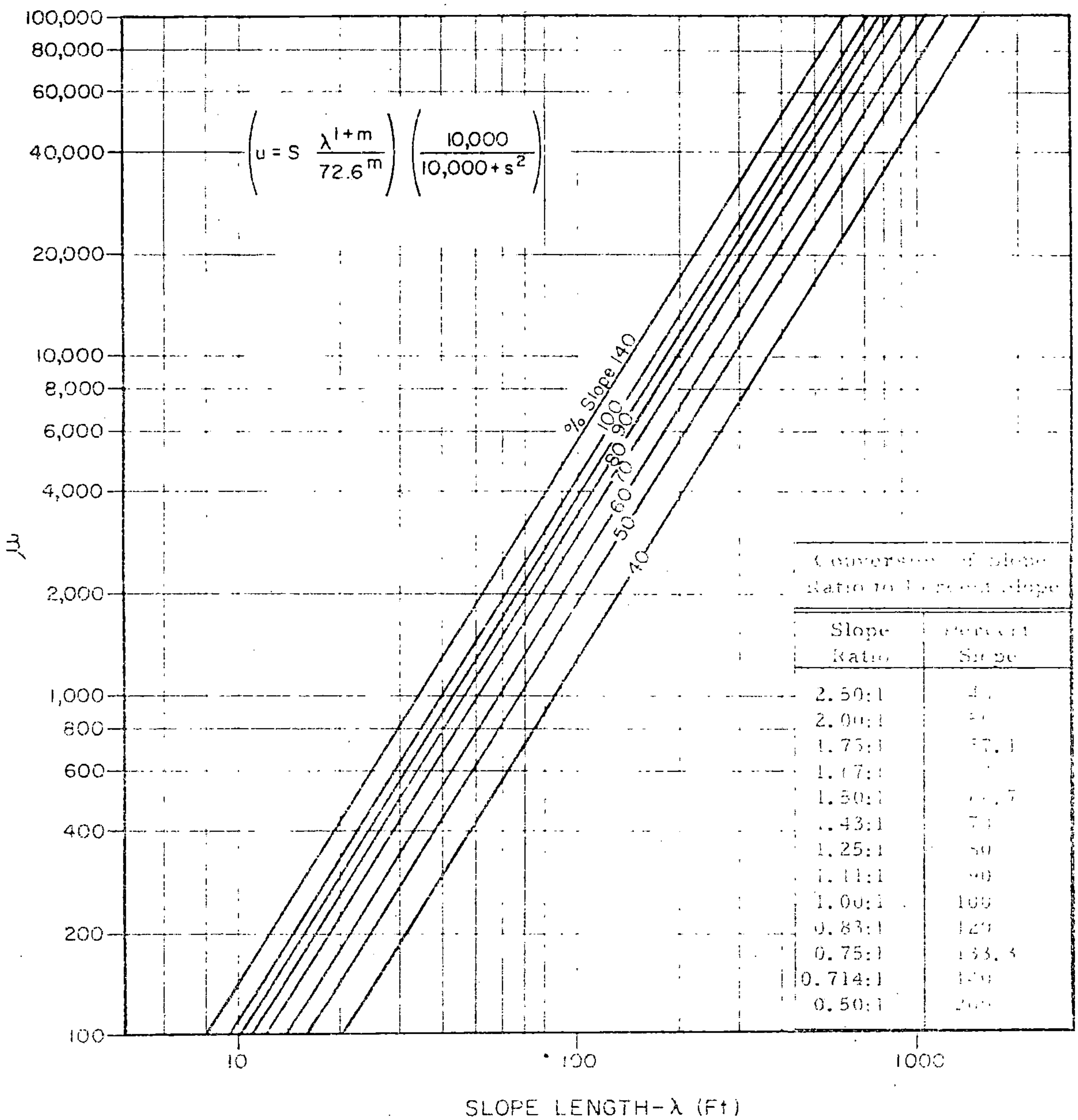


Figure E-1. Values of u for use with multiple slopes (2-10%).
(m = 0.5)



Slope Ratio	Percent Slope
10:1	10.0
8.33:1	12.0
8.0:1	12.5
7.14:1	14.0
6.25:1	16.0
6.0:1	16.7
5.56:1	18.0
5.0:1	20.0
4.0:1	25.0
3.50:1	28.6
3.33:1	30.0
3.00:1	33.3
2.86:1	35.0
2.5:1	40.0

Figure E-2. Values of u for use with multiple slopes (10-40%). (m = 0.6)



Conversion of Slope Ratio to Percent Slope

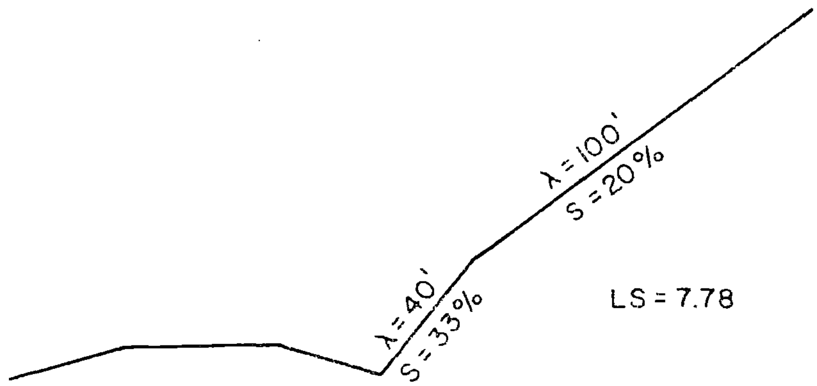
Slope Ratio	Percent Slope
2.50:1	[illegible]
2.00:1	[illegible]
1.75:1	[illegible]
1.67:1	[illegible]
1.50:1	[illegible]
.43:1	[illegible]
1.25:1	[illegible]
1.11:1	[illegible]
1.00:1	100
0.83:1	[illegible]
0.75:1	133.3
0.714:1	[illegible]
0.50:1	[illegible]

Figure E-3. Values of u for use with multiple slopes (40-140%). (m = 0.6)

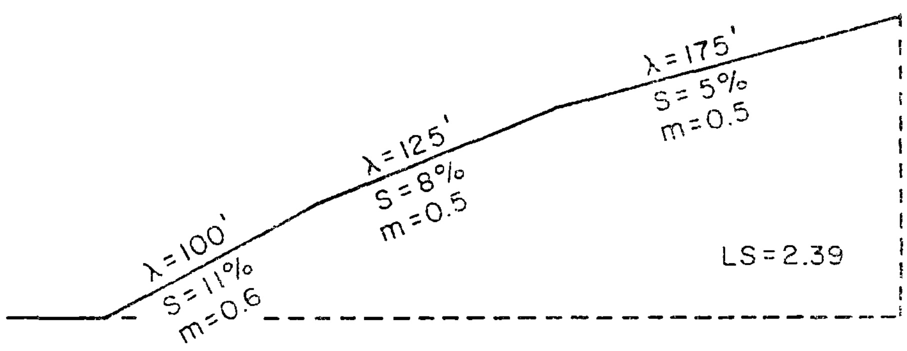
The percentage of the total sediment yield that comes from each of the n slope segments is also obtained by this computational procedure. The relative sediment contribution of segment j is $(u_{2j} - u_{1j}) / \sum_{j=1}^{n} (u_{2j} - u_{1j})$.

Calculating LS values. To illustrate the procedure, assume the 400-foot convex slope represented by Curve A in Figure E-4. The upper segment is 175 feet at 5 percent gradient, the second is 125 feet at 8 percent, and the lower segment is 100 feet at 11 percent. Thus the λ (slope length in feet) values are: $\lambda_1 = 175$, $\lambda_2 = 300$, $\lambda_3 = 400 = \lambda_e$. For the first segment, enter Figure E-1 at 175 on the horizontal axis, move upward to the curve for 5 percent slope, and read $u_2 = 123$ on the vertical scale. The upper end of this segment is at zero length, so $u_2 - u_1 = 123$. For the second segment use the curve for 8 percent slope, entering the graph with lengths of 300 feet and 175 feet. For these, $u_2 = 512$, $u_1 = 228$, and $u_2 - u_1 = 284$. Each segment LS value is determined by dividing the $(u_2 - u_1)$ value by the segment length. Dividing each $(u_2 - u_1)$ value by the sum of $(u_2 - u_1)$ values gives the percent of total sediment contributed by each slope segment. Only Figures E-1, E-2 and simple arithmetic are needed to complete the following tabulation.

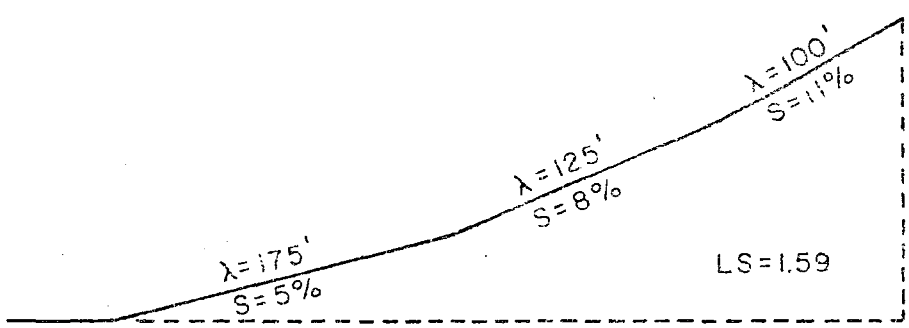
Segment	λ_j	λ_{j-1}	u_2	u_1	u_2-u_1	Segment Length	Segment LS	% of Total Sediment
1	175	0	123	0	123	175	0.70	13
2	300	175	512	228	284	125	2.27	30
3	400	300	1485	938	547	100	5.47	57
Entire slope					954	400	2.39	100



GENERAL HIGHWAY CROSS-SECTION
Cut on right with two slopes



CURVE A. CONVEX SLOPE



CURVE B. CONCAVE SLOPE

Figure E-4. Typical slopes used to illustrate computational procedure for LS.

The overall LS value of 2.39 shown in the second column from the right may have been the principal objective of the computations. This was obtained by dividing the sum of the $(u_{2j} - u_{1j})$ by the total slope length (954/400 = 2.39). However, the detail provided by the last two columns of the tabulation will be helpful for designing the most effective erosion-control practices on those slope segments where the hazard is greatest. For instance, a diversion berm or ditch immediately above the lower 100-foot segment of Curve A, Figure E-4, would reduce the effective LS on that segment from 5.47 to 1.6. Constructing the berm at the midpoint of the 400-foot slope would reduce LS on the last 100-foot segment to only 2.2.

The effective LS for any segment is obtained by dividing $(u_2 - u_1)$ for that segment by the length of the segment, as illustrated. The predicted <u>rate</u> of soil loss per unit area for the slope segment equals this LS value times the appropriate values of the equation's factors R, K, and VM.

The last column shows the portion of the total sediment yield that comes from each of the slope segments. The relative sediment contribution of segment j is $(u_{2j} - u_{1j}) / \sum_{j=1}^{n} (u_{2j} - u_{1j})$. For example, segment 3 in the above example contributes 547/954 = 57 percent of the total sediment load. Sources of the data in the other columns of the tabulation have been previously explained.

Applying the above procedure to the concave slope B of Figure E-4 gives an LS value of 1.59 in contrast to the 2.39 obtained for the convex slope A. The LS factor for a 400-foot uniform slope of the same average steepness (7.5 percent) is 1.80.

If we assume that R = 200, K = 0.49, and VM = 0.25 on the entire slope (RK VM = 24.5 T/ac), we obtain the following predictions of rates of soil-loss for the three slopes in the example, each of which averages 7.5 percent:

Uniform, 1.80 x 24.5 = 44.1 T/A

Convex, 2.39 x 24.5 = 58.6 T/A--(requires least excavation)

Concave, 1.59 x 24.5 = 39.0 T/A--(requires most excavation)

Graphically determining LS values. The topographic factor LS for multiple slopes can be determined also by using a straight edge and the triangular nomograph shown in Figure 5-11. The following example refers to the general highway cross section shown in Figure E-4 and proceeds as follows:

1. Lay a straight edge on the nomograph between the 100 foot slope length and the 20 percent slope gradient, and mark the corresponding LS value.

2. Rotate the straight edge around this LS value until the slope gradient reads 33 percent. Note the corresponding slope length which is 25.

3. Add the two slope lengths (40 and 25) to obtain a new equivalent slope length of 65 feet at 33 percent slope gradient.

4. Enter the nomograph with the values of 33 percent and 65 feet and read the LS value for the combined slopes of 7.6 (the Wischmeier Foster equation gives a value of 7.78).

Effect of soil erodibility factor. The soil erodibility factor, K, may vary substantially from the upper to the lower part of a slope. This is particularly likely for constructed slopes that cut through successive soil horizons. When differences in slope steepness are associated with differences in soil along an irregular slope, accuracy of sediment prediction is improved by combining the two variables on a segmental basis. This can be done if the factor K is brought into the summation as K_j in the equation (31)

$$A = R\ VM\ (1/\lambda_e) \sum_{j=1}^{n} K_j\ (u_{2j} - u_{1j})$$

Suppose that in the preceding illustration for the convex slope the upper 175-foot segment was on a soil horizon for which K = 0.49 and the other two segments on a horizon for which K = 0.32. The $(u_{2j} - u_{1j})$ values in the computation would have been multiplied by the corresponding K values before summing.

$$
\begin{aligned}
123 \times 0.49 &= 60.3 \\
284 \times 0.32 &= 90.9 \\
547 \times 0.32 &= \underline{175.0} \\
& \quad 326.2
\end{aligned}
$$

KLS = 326.2/400 = 0.816. A = 0.816R VM = 40.8 T/ac.

Had the two K values been reversed in their positions on the slope, KLS would have been 1.12, and the predicted soil loss would have been 55.8 T/ac.

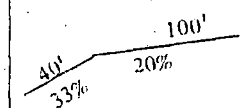
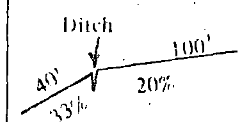
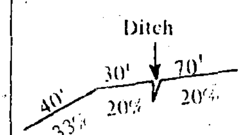
Effect of ditches or berms. Utilizing the tabular method presented in Table E-1, one may readily determine the amounts of sediment contributed by the various segments of a compound slope, and how these amounts may be altered. The installation of a berm or a diversion ditch serves to shorten the slope and thus decreases its erosion potential. The following step by step procedure will illustrate the use of the table. Values shown were obtained from graphs presented in Figures E-1, E-2, and E-3, and from the highway cross section in Figure E-4 for a location in northwestern Missouri. The rainfall (R) factor value is 165 and the soil erodibility (K) factor is 0.30.

1. Enter in columns 2, 3, and 7 the appropriate slope segment lengths from Figure E-4, remembering that λ_j is the segment nearest the top where water first enters the slope.

2. From Figures E-1, E-2, and E-3 determine the appropriate u values and enter them in columns 4 and 5.

3. Calculate the u differences for each segment and the sum of differences of all segments (column 6). These values divided by the appropriate slope lengths give the LS value for each segment and for the total slope (column 8).

Table E-1. Effect of slope length and steepness on soil loss potential.

1		2	3	4	5	6	7	8	9	10	11	12	13	14
		λ_j	λ_{j-1}	u_2	u_1	u_2-u_1	Segment Length (ft)	Segment LS (Col. 6/7)	$\frac{u_2-u_1}{43,560}$	K	R	A=RK LS (T/acre/year)	A=RK Col. 9 (T/ft. of slope width)	Sketch
								Example 1—without diversion ditch						
1	20	100	0	416	0	416	100	4.16	0.00955	0.30	165	205.9	0.473	
2	33	140	100	1618	945	673	40	16.83	0.01545	0.30	165	832.8	0.765	
						1089	140	7.78	0.02500	0.30	165	385.1	1.238	
								Example 2—Diversion ditch at break in slope						
1	20	100	0	416	0	416	100	4.16	0.00955	0.30	165	205.9	0.473	
2	33	40	0	218	0	218	40	5.45	0.00501	0.30	165	269.8	0.248	
						634	140	4.53	0.01456	0.30	165	224.1	0.721	
								Example 3—Diversion ditch on upper slope						
1	20	70	0	235	0	235	70	3.36	0.00540	0.30	165	166	0.267	
2	20	30	0	61	0	61	30	2.03	0.00139	0.30	165	101	0.069	
3	33	70	30	534	138	396	40	9.90	0.00910	0.30	165	490	0.450	
						692	140	4.94	0.01589	0.30	165	245	0.786	

4. Enter the proper K value in column 10.

5. Insert the proper R values in column 11. These can be determined from Figure 5-1 for mean annual values or from the distribution curves in Figure 5-5 for monthly values.

6. Sometimes a more meaningful evaluation can be made by comparing erosion rates per unit width of slope than erosion per unit area of right-of-way. To obtain values for erosion in tons per year per foot of slope width, divide column 6 by 43560 (see column 9) and multiply by the R and K values (columns 10 and 11). These products appear in column 13.

7. The LS values are determined by dividing the values of $u_2 - u_1$ in column 6 by the slope lengths in column 7. The erosion rate in tons/acre is then calculated by multiplying by values of R and K (column 12).

The procedures illustrated herein may be applied to any structures that control on-site rill and sheet erosion such as ditches or berms used to keep overland flow off a lower-lying slope. The effects of ditches and berms are reflected in the LS factor in the water soil erosion equation and not in the VM factor.

The erosion rate can be reduced by reducing the LS factor. One effective way of doing this is by constructing a diversion ditch or berm to prevent the flow of water from an upper slope from entering the lower

slope. Calculations to demonstrate this effect are shown in examples 2 and 3 in Table E-1. The slope lengths are treated in the same way as in the first example, the ditch effectively reducing the length of the lower slope. By placing the ditch at the top of the lower slope the potential erosion rate is reduced to 58 percent of that without a ditch. Placing the ditch part way up on the upper slope so as to divide the total slope into 2 equal lengths decreases the rate to only 63 percent of its previous value as shown in the third calculation in Table E-1.

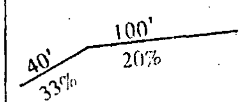
EROSION CONTROL FACTOR VM

An erosion control measure used effectively reduces the potential erosion rate, A, by the factor **VM**. Because most erosion control measures take time to implement, and become more effective with time, they should be evaluated on a time basis. Tables E-2 and E-3 will illustrate this point.

Values of $u_2 - u_1/43,560$ and of K and λ are taken from Table E-1 and entered into the appropriate columns of Tables E-2 and E-3. R values are determined from the distribution curves of Figure 5-5. Computations are made to complete column 6. Values of VM are taken from Table 5-2 for the indicated erosion control measures, and column 8 values are calculated.

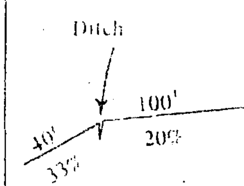
The example presented in Table E-3 is indentical to that in Table E-2 except that a diversion ditch was installed at the top of the lower slope

Table E-2. Effect of timing of implementation of erosion control measures.

1	2	3	4	5	6	7	8	9	10
Time Period	λ	R	K	$\frac{U_2-U_1}{43,560}$	A = RK x Col. 5 (Tons/ft width of slope)	(VM)	A = RKVM x Col. 5 (Tons/ft width of slope)	Kinds and Timing of Treatments	Sketch of Slopes
Sept.	140	18.15	0.30	0.0250	0.1361	1.20	0.1633	Bare soil, bulldozer compacted, scraped across slope, start Sept. 1	
Oct.	140	8.25	0.30	0.0250	0.0619	1.20	0.0743	"	
Nov.	140	1.65	0.30	0.0250	0.0124	1.20	0.0149	"	
Dec.	140	1.65	0.30	0.0250	0.0124	0.01	0.0001	Covered with top soil, seeded, straw mulch punched in across slope	
Jan.	140	1.65	0.30	0.0250	0.0124	0.01	0.0001	"	
Feb.	140	1.65	0.30	0.0250	0.0124	0.01	0.0001	"	
Mar.	140	1.65	0.30	0.0250	0.0124	0.01	0.0001	"	
Apr.	140	6.60	0.30	0.0250	0.0495	0.01	0.0005	Early grass growth	
May	140	19.80	0.30	0.0250	0.1485	0.01	0.0015	"	
June	140	46.20	0.30	0.0250	0.3465	0.01	0.0035	"	
July	140	29.70	0.30	0.0250	0.2228	0.01	0.0022	Established grass	
Aug.	140	28.05	0.30	0.0250	0.2104	0.01	0.0021	"	
Total	140	165.0			1.2501		0.2627		

Note: It is interesting to observe that if the start of construction were delayed until Nov. 1, most of the erosion potential would be eliminated.

Table E-3. Effect of timing of implementation of erosion control measures, with diversion ditch.

1	2	3	4	5	6	7	8	9	10
Time Period	λ	R	K	$\frac{U_2-U_1}{43,560}$	A = RK x Col. 5 (Tons/ft width of slope)	(VM)	A = RKVM x Col. 5 (Tons/ft width of slope)	Kinds and Timing of Treatments	Sketch of Slopes
Sept.	140	18.15	0.30	0.02500	0.1361	1.20	0.1633	Bare soil, bulldozer compacted, scraped across slope, start Sept. 1 (diversion ditch installed at top of lower slope on October 1)	
Oct.	100 40	8.25	0.30	0.00955 0.00501	0.0236 0.0124	1.20 1.20	0.0284 0.0144	"	
Nov.	100 40	1.65	0.30	0.00955 0.00501	0.0047 0.0025	1.20 1.20	0.0057 0.0030	"	
Dec.	100 40	1.65	0.30	0.00955 0.00501	0.0047 0.0025	0.01 0.01	-- --	Covered with top soil, seeded, straw mulch punched in across slope	
Jan.	100 40	1.65	0.30	0.00955 0.00501	0.0047 0.0025	0.01 0.01	-- --	"	
Feb.	100 40	1.65	0.30	0.00955 0.00501	0.0047 0.0025	0.01 0.01	-- --	"	
Mar.	100 40	1.65	0.30	0.00955 0.00501	0.0047 0.0025	0.01 0.01	-- --	"	
Apr.	100 40	6.60	0.30	0.00955 0.00501	0.0189 0.0099	0.01 0.01	0.0002 0.0001	Early grass growth	
May	100 40	19.80	0.30	0.00955 0.00501	0.0564 0.0298	0.01 0.01	0.0006 0.0003	"	
June	100 40	46.20	0.30	0.00955 0.00501	0.1324 0.0694	0.01 0.01	0.0013 0.0007	"	
July	100 40	29.70	0.30	0.00955 0.00501	0.0851 0.0046	0.01 0.01	0.0009 0.0004	Established grass	
Aug.	100 40	28.05	0.30	0.00955 0.00501	0.0804 0.0422	0.01 0.01	0.0008 0.0004	"	
Total	140	165			0.7772		0.2210		

soon after construction was begun. The effectiveness of the ditch has been substantially reduced by the effects of rainfall during the first month of construction before the ditch was installed. Erosion control measures in both examples were applied according to the following schedule and with the VM factor values indicated.

Erosion Control Schedule

1.	Bare soil, no erosion controls	3 months
2.	Straw mulch	4 months
3.	Early grass growth, with mulch	3 months
4.	Established permanent grass	2 months

VM Factors

	Description of Factor	Source of Value	Factor Value
1.	Bare soil, bulldozer compacted and scraped across slope	Table 5-2	1.20
2.	Straw mulch, punched in, across slope, 2.5 tons/acre	Figure 5-13 (results from literature)	0.01
3.	Early grass growth with mulch described in number 2	Use mulch value	0.01

It is interesting to note that, in both examples, if the beginning of construction were delayed two months (November 1 instead of

September 1, most of the erosion potential would be eliminated because of the smaller values of R existing at that time of the year.

The tabular method of calculation presented herein enables one to readily determine the effects of individual slope segments, differing soil erodibility values of different slope segments, monthly variations in the value of R and of shortening slopes with ditches or berms.

In cases where a knowledge of the intermediate steps is not required, values of LS may be determined directly from the nomograph in Figure E-11 and inserted in the table. A second nomograph, Figure B-1 in Appendix B, solves the soil loss equation, A = RKLS, directly. This value must be multiplied by a VM factor to include effects of erosion control measures.

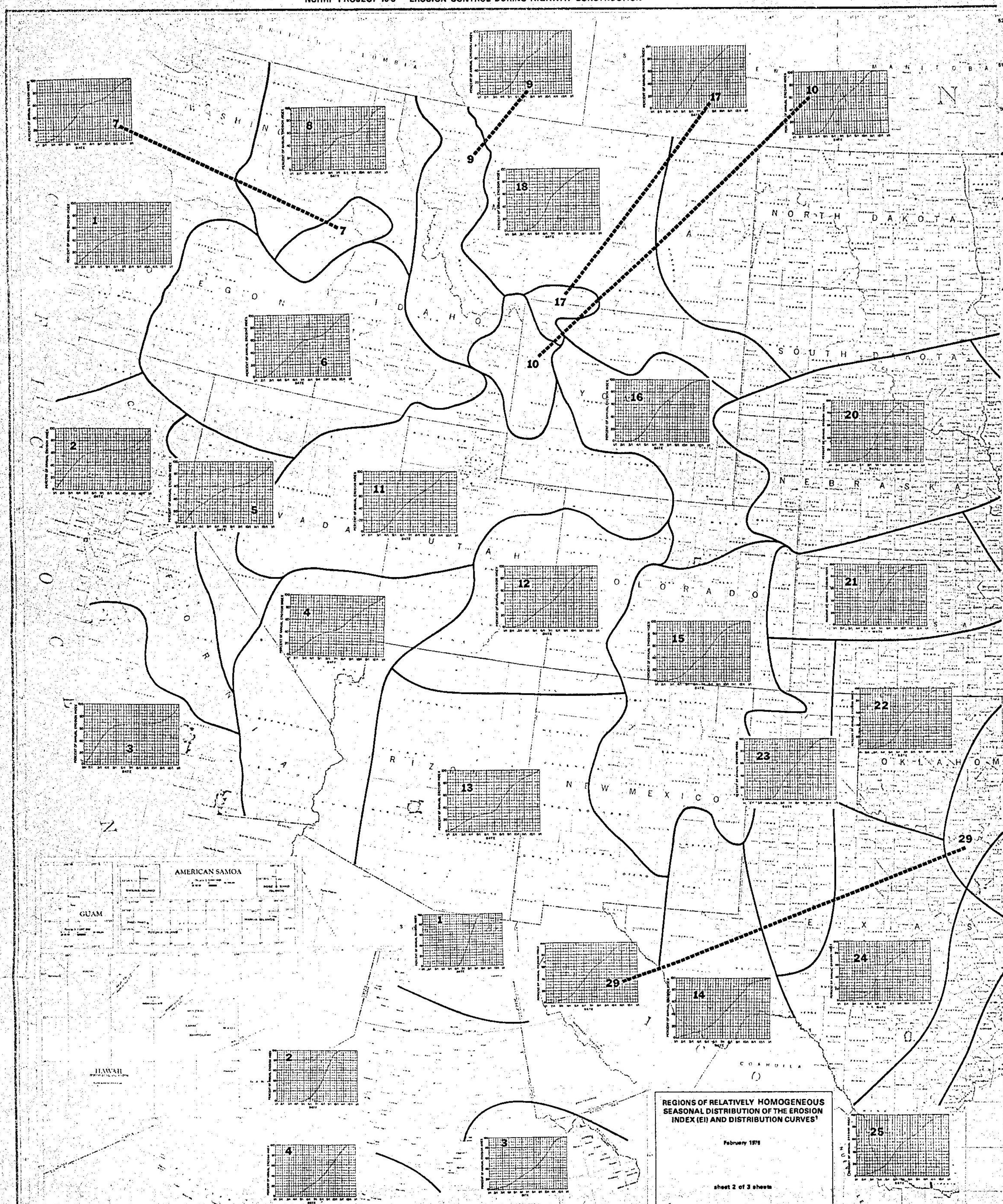
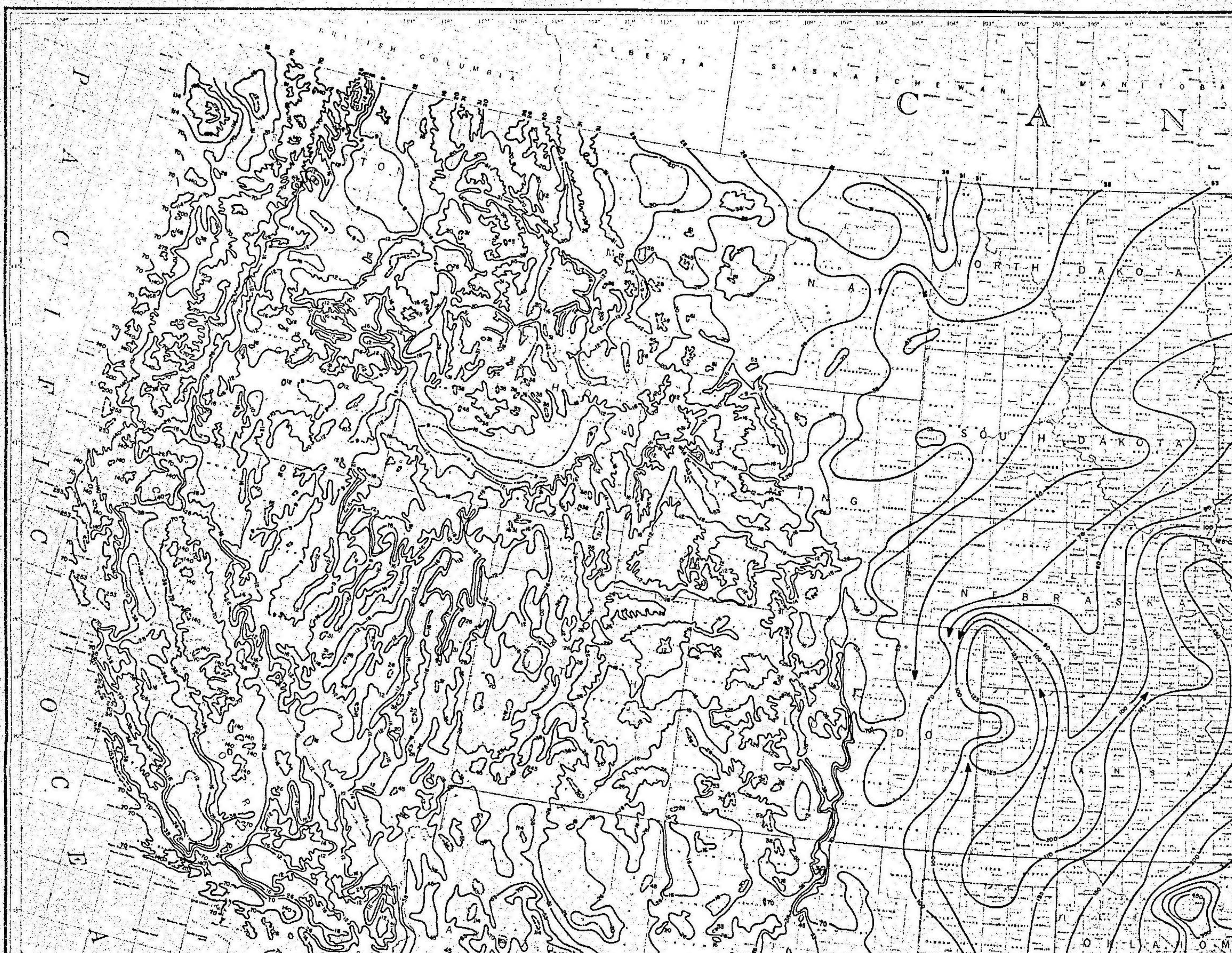


Figure 5-5 EROSION INDEX (EI) DISTRIBUTION CURVES
WESTERN UNITED STATES AND ALASKA

Figure 5-5 EROSION INDEX (EI) DISTRIBUTION CURVES



WESTERN UNITED STATES AND ALASKA

Figure 5-2 ISO-ERODENT (R) VALUES

APPENDIX II

SCS METHOD FOR COMPUTING STORM RUNOFF HYDROGRAPHS

(Excerpted from U.S. Soil Conservation Service, 1972)

RAINFALL SEQUENCE

Rainfall amount, duration, intensity and variations of intensity during a storm are most important to storm runoff determinations because of their relation to retention losses discussed above.

Amount of Rainfall

All hydrologic analyses require a determination of the average depth of storm rainfall over an area. The average depth may be computed in various ways, depending on the data used. These methods are well-known to hydrologists, and are presented in many textbooks on hydrology.

Storm Duration

An estimate of the total duration of a storm or series of storms is required for estimating peak rates of runoff, or in developing storm hydrographs.

Natural Storms (SCS, 1972)

Duration of specific actual storms can generally be estimated to the nearest hour by use of Weather Bureau publications of hourly precipitation data. With these data, or even with instrument charts from a recording gage, it is often difficult to decide on the beginning or ending times of a storm. Furthermore, if there are periods of no rain within the storm, the duration may need to be arbitrarily defined. The problem of hydrograph construction is simplified by using storm increments and, in general, this is the best way of using natural storms.

Figure 4.10 illustrates a typical natural storm for which the storm duration must be arbitrarily defined. The figure shows the accumulated runoff occurring when the runoff curve numbers 1/ of 100, 80 and 70 are applicable. Note that the duration of excessive rainfall, which is the rainfall producing the runoff, is always less than the storm duration except when runoff is 100 percent. Since the duration of excessive rainfall is the correct duration to use with peak rate equations, such equations will be more successful with natural storms that are brief and intense. Hydrologic design methods have been developed to account for the initial abstraction, so that duration of excessive rainfall is used.

Effective Duration (D_e)

When standard gage data are used in a watershed project evaluation, the storm durations will usually be unknown. An approximate duration for use with all the storms can be estimated using figure 4.11, which shows the relation between average annual rainfall and an "effective duration". The gage rainfalls are used as if they had fallen in D_e hours.

1/ See SCS National Engineering Handbook for discussions of runoff curve numbers.

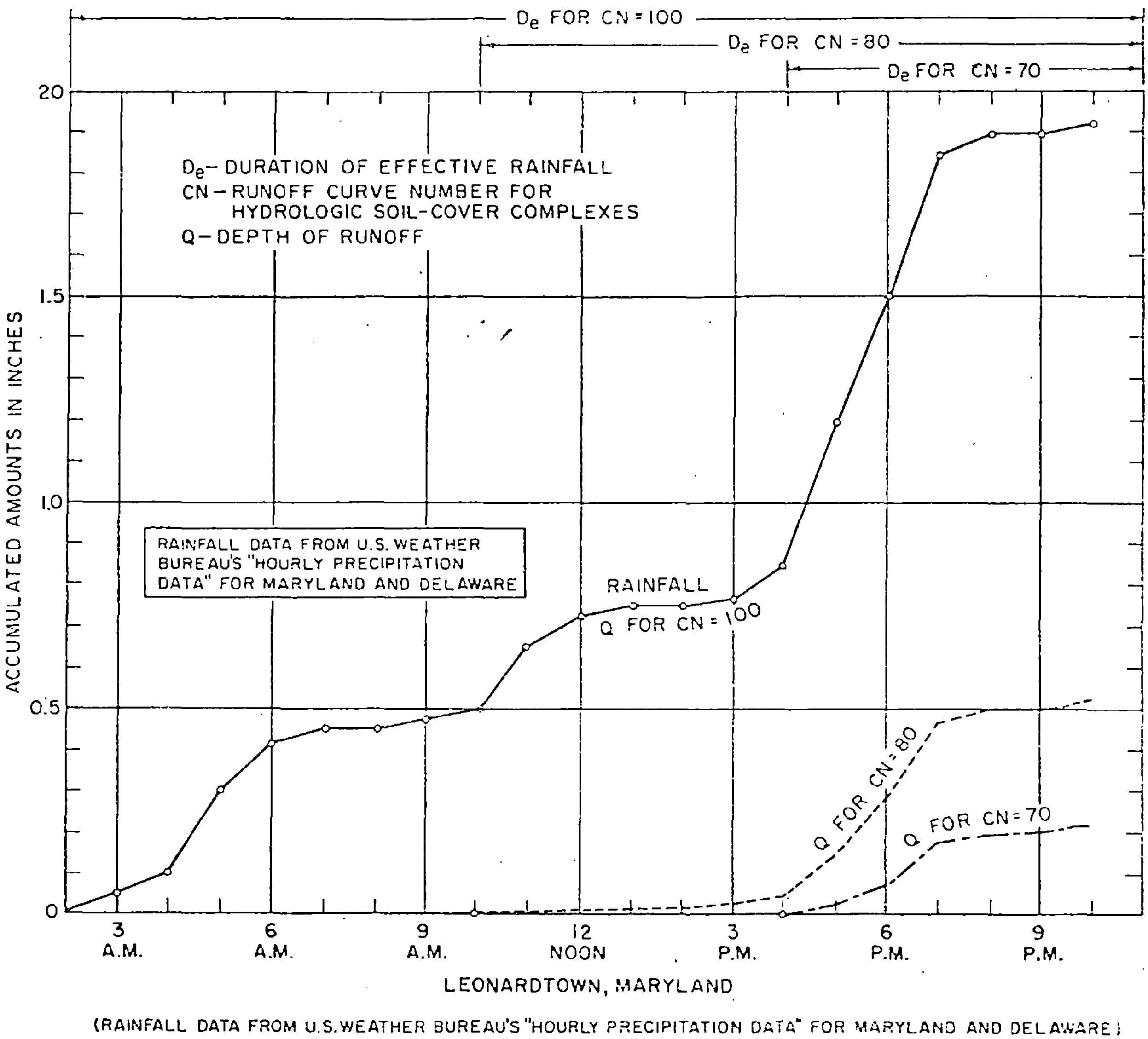


Figure 4.10.--Effect of hydrologic soil-cover complex on duration of effective rainfall.

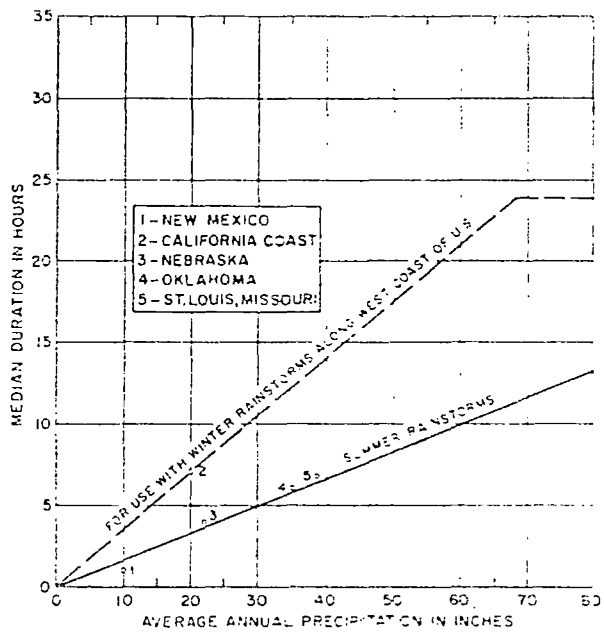


Figure 4.11.--Graph for estimating effective duration.

Rainfall Distribution

(a) Short-interval estimates of the distribution of thunderstorm rainfall are difficult to make, since field data for such events are meager. In the absence of adequate field data, the hydrologist is forced to assume a time sequence for short-duration storms. An example of 15-minute time sequences recommended by the USBR (1974) for design thunderstorms is shown in Table A-8. After design thunderstorm precipitation values have been arranged in respective time-sequence magnitude, direct runoff increments are computed using equation (10.8).

(b) Longer-interval estimates of rainfall distribution can be made by direct analyses of field data, or by alternate methods in the absence of such information. One such method, used by the Soil Conservation Service (1972) is summarized in Table 21.5. This summary is for a 10-day period and is based on SCS experience in developing guidelines for computing design hydrographs.

Table A-8. Design thunderstorm precipitation time-sequence in 15-minute intervals

Time, hour	Order of magnitude	
	Zones I and III	Zone II
0.0..................	0	0
0.25..................	4	3
.50..................	3	2
.75..................	2	1
1.00..................	1	4
1.25..................	5	
1.50..................	6	
1.75..................	7	
2.00..................	8	
2.25..................	9	
2.50..................	10	
2.75..................	11	
3.00..................	[1] 12	

1 Duration limit of zone rainfall.

Table 21.5.--Arrangement of increments before construction of PSH and PSMC

Time	Increment
days	
0.0 to 0.5	19th largest ½ day
0.5 to 1.0	17th largest ½ day
1.0 to 1.5	15th largest ½ day
1.5 to 2.0	13th largest ½ day
2.0 to 2.5	11th largest ½ day
2.5 to 3.0	9th largest ½ day
3.0 to 3.5	7th largest ½ day
3.5 to 4.0	5th largest ½ day
4.0 to 4.5	3rd largest ½ day
4.5 to 4.6	9th largest 1/10 day
4.6 to 4.7	7th largest 1/10 day
4.7 to 4.8	5th largest 1/10 day
4.8 to 4.9	3rd largest 1/10 day
4.9 to 5.0	Largest 1/10 day
5.0 to 5.1	2nd largest 1/10 day
5.1 to 5.2	4th largest 1/10 day
5.2 to 5.3	6th largest 1/10 day
5.3 to 5.4	8th largest 1/10 day
5.4 to 5.5	10th largest 1/10 day
5.5 to 6.0	4th largest ½ day
6.0 to 6.5	6th largest ½ day
6.5 to 7.0	8th largest ½ day
7.0 to 7.5	10th largest ½ day
7.5 to 8.0	12th largest ½ day
8.0 to 8.5	14th largest ½ day
8.5 to 9.0	16th largest ½ day
9.0 to 9.5	18th largest ½ day
9.5 to 10.0	20th largest ½ day

Other methods are available for computing longer-interval storm rainfall time distributions based on comprehensive analyses of rainfall patterns in large river basins (see Frederick, 1973, and Weather Bureau Technical Paper No. 49, by Miller 1964).

HYDROGRAPH GENERATION

Many methods exist for computing hydrographs from direct runoff inputs, and an in-depth review of this aspect of forest hydrology is beyond the scope of this report. Procedures available to the hydrologist vary in complexity and sophistication, depending on the level of analysis desired, and the availability of computing hardware.

Because many of the responses associated with silvicultural activities are tied to the runoff hydrograph, serious attention should be given to converting the computed generated runoff volumes to streamflow. Two approaches are discussed herein; however, they are by no means superior to other available methods for computing the hydrograph.

UNIT HYDROGRAPH

The unit hydrograph (Sherman, 1940) is an old-timer in engineering hydrology. Its use as a powerful hydrologic tool is perhaps best summarized by Mitchell (1948):[1]

> There has been developed no rigorous theory by which the unit hydrograph relations may be proven. However, the results which have been obtained by a judicious application of the relationship have been so predominately satisfactory that there can be no doubt that it is indeed a tool of considerable value for resolving to some extent the complex relations of rainfall and runoff and for advancing the science of hydrology.

"A unit hydrograph is a discharge hydrograph resulting from one inch of direct runoff generated uniformly over the tributary area at a uniform rate during a specified period of time." (Gray 1970). The basic principles of unit hydrograph theory are as follows (Gray, 1970):

The theory is based in principle on the criteria (Johnstone and Cross, 1949):

1. For a given watershed, runoff producing storms of equal duration will produce surface runoff hydrographs with approximately equivalent time bases, regardless of the intensity of the rain.

1/ quote from Gray (1970).

2. For a given watershed, the magnitude of the ordinates representing the instantaneous discharge from an area will be proportional to the volumes of surface runoff produced by storms of equal duration.

3. For a given watershed, the time distribution of runoff from a given storm period is independent of precipitation from antecedent or subsequent storm periods.

Unit hydrographs can be derived for a watershed from streamflow data. and these methods are discussed in most hydrology textbooks (for example, see Wisler and Brater, 1959; Gray, 1970; and SCS, 1972). In the absence of adequate field data, hydrologists have developed the so-called "Synthetic Unit Hydrograph", for storm runoff which is based on watershed parameters and rainfall characteristics. If the watershed parameters are modified in any way as the result of silvicultural activities, these changes, coupled with changes in direct runoff (equation (10.8)) can be used to estimate the impact of streamflow. The following material is quoted from the SCS National Engineering Handbook

(SCS, 1972), and outlines procedures for computing synthetic uni-

hydrographs:

> The fundamental principles of invariance and superposition make the unit graph an extremely flexible tool for developing synthetic hydrographs: (1) the hydrograph of surface runoff from a watershed due to a given pattern of rainfall is invariable, and (2) the hydrograph resulting from a given pattern of rainfall excess can be built up by superimposing the unit hydrograph due to the separate amounts of rainfall excess occurring in each unit period. This includes the principle of proportionality by which the ordinates of the hydrograph are proportional to the volume of rainfall excess.
>
> The unit time or "unit hydrograph duration" is the optimum duration for occurrence of precipitation excess. In general, this unit time is approximately 20 percent of the time interval between the beginning of runoff from a short high-intensity storm and the peak discharge of the corresponding runoff.
>
> The "storm duration" is the actual duration of the precipitation excess. The duration varies with actual storms. The dimensionless unit hydrograph used by SCS (figure 16.1) was developed by Victor Mockus. It was derived from a large number of natural unit hydrographs from watersheds varying widely in size and geographical locations. This dimensionless curvilinear hydrograph, also shown in table 16.1, has its ordinate values expressed in a dimensionless ratio q/q_p or Qa/Q and its abscissa values as t/T_p. This unit hydrograph has a point of inflection approximately 1.70 times the time-to-peak (T_p) and the time-to-peak 0.2 of the time-of-base (T_b).

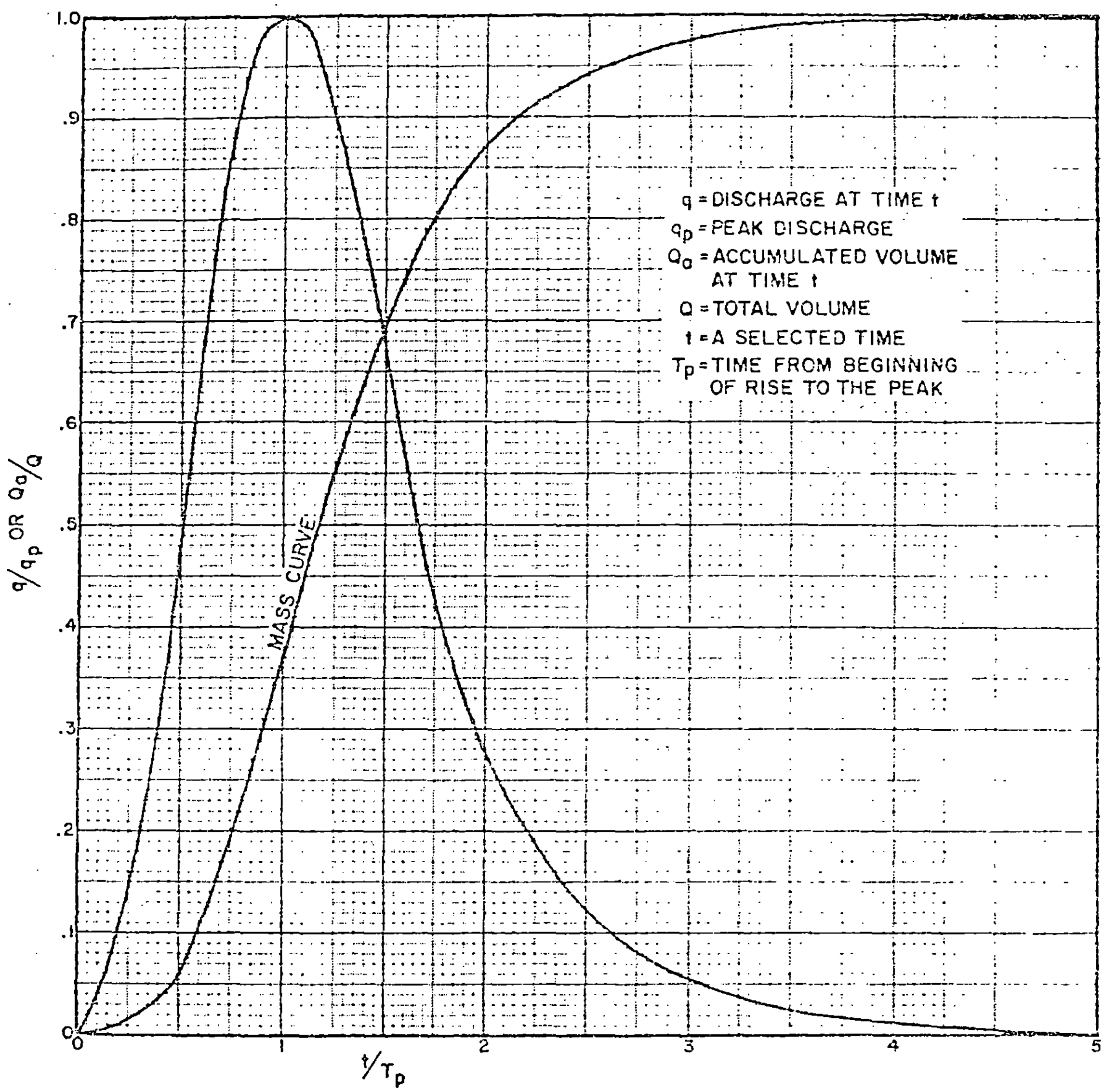


Figure 16.1 Dimensionless unit hydrograph and mass curve

Table 16.1 Ratios for dimensionless unit hydrograph and mass curve.

Time Ratios (t/T_p)	Discharge Ratios (q/q_p)	Mass Curve Ratios (Q_a/Q)
0	.000	.000
.1	.030	.001
.2	.100	.006
.3	.190	.012
.4	.310	.035
.5	.470	.065
.6	.660	.107
.7	.820	.163
.8	.930	.228
.9	.990	.300
1.0	1.000	.375
1.1	.990	.450
1.2	.930	.522
1.3	.860	.589
1.4	.780	.650
1.5	.680	.700
1.6	.560	.751
1.7	.460	.790
1.8	.390	.822
1.9	.330	.849
2.0	.280	.871
2.2	.207	.908
2.4	.147	.934
2.6	.107	.953
2.8	.077	.967
3.0	.055	.977
3.2	.040	.984
3.4	.029	.989
3.6	.021	.993
3.8	.015	.995
4.0	.011	.997
4.5	.005	.999
5.0	.000	1.000

Elements of a Unit Hydrograph

The dimensionless curvilinear unit hydrograph (figure 16.1) has 37.5% of the total volume in the rising side, which is represented by one unit of time and one unit of discharge. This dimensionless unit hydrograph also can be represented by an equivalent triangular hydrograph having the same units of time and discharge, thus having the same percent of volume in the rising side of the triangle (figure 16.2).

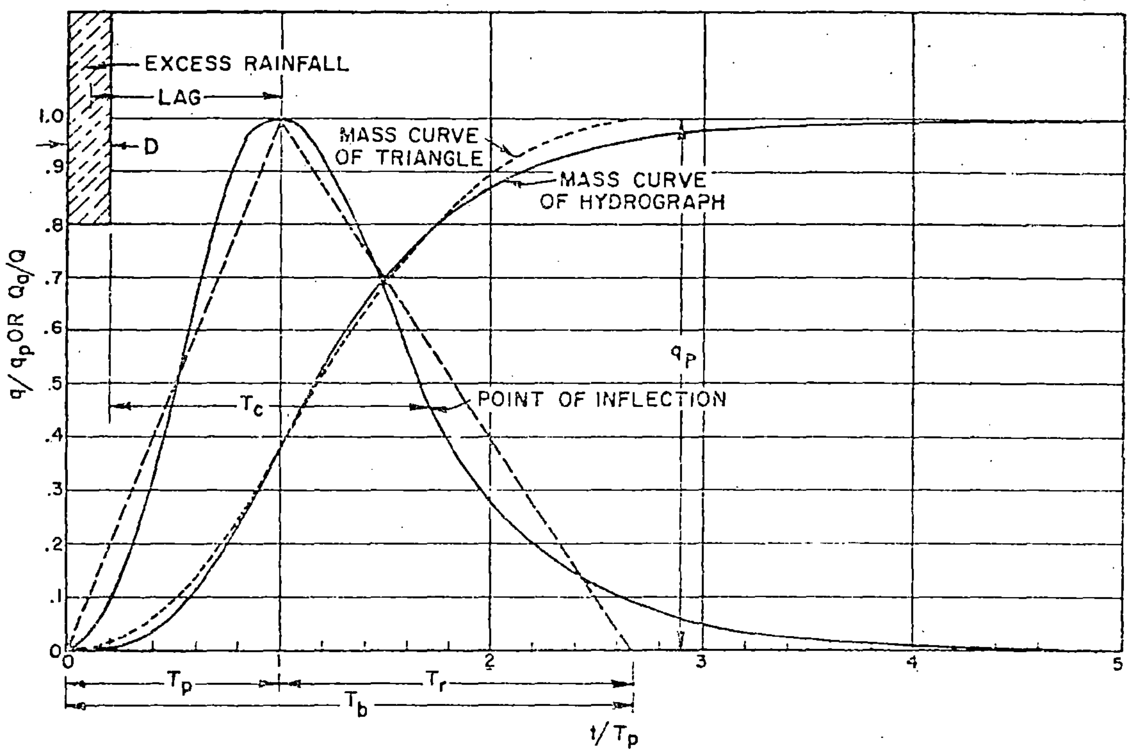


Figure 16.2 Dimensionless curvilinear unit hydrograph and equivalent triangular hydrograph

D will be .2 T_p. A small variation in D is permissible, however, it should be no greater than .25 T_p.

Using the relationship shown on the dimensionless unit hydrograph, figure 16.2 to compute the relationship of D to T_c:

$$T_c + D = 1.7\ T_p \qquad \text{(Eq. 16.10)}$$

$$\frac{D}{2} + .6\ T_c = T_p \qquad \text{(Eq. 16.11)}$$

Solving these two equations:

$$T_c + D = 1.7\ (\frac{D}{2} + .6\ T_c)$$

$$.15\ D = .2\ T_c$$

$$D = .133\ T_c \qquad \text{(Eq. 16.12)}$$

Computation of hydrographs for ungaged watersheds is contingent on an estimate of T_c. Various methods of estimating this parameter are available to the hydrologist. Several are summarized in chart form in Figure 30 (USBR, 1974). If data are available, the USBR (1974) suggests that more than one method of estimating time of concentration be used in deriving a representative value for a given watershed.

This allows the base of the triangle to be solved in relation to the time to peak using the geometry of triangles. Solving for the base length of the triangle, if one unit of time T_p equals .375 of volume:

$$T_b = \frac{1.00}{.375} = 2.67 \text{ units of time,}$$

$$T_r = T_b - T_p = 1.67 \text{ units of time or } 1.67\ T_p.$$

These relationships are useful in developing the peak rate equation for use with the dimensionless unit hydrograph.

Peak Rate Equation

From figure 16.2 the total volume under the triangular unit hydrograph is:

$$Q = \frac{q_p\ T_p}{2} + \frac{q_p\ T_r}{2} = \frac{q_p}{2}(T_p + T_r) \qquad \text{(Eq. 16.1)}$$

With Q in inches and T in hours, solve for peak rate q_p in inches per hour:

$$q_p = \frac{2Q}{T_p + T_r} \qquad \text{(Eq. 16.2)}$$

$$\text{Let} \quad K = \frac{2}{1 + \frac{T_r}{T_p}} \qquad \text{(Eq. 16.3)}$$

$$\text{Therefore} \quad q_p = \frac{KQ}{T_p} \qquad \text{(Eq. 16.4)}$$

In making the conversion from inches per hour to cubic feet per second and putting the equation in terms ordinarily used, including drainage area "A" in square miles, and time "T" in hours, equation 16.4 becomes the general equation:

$$q_p = \frac{645.33 \times K \times A \times Q}{T_p} \qquad \text{(Eq. 16.5)}$$

Where q_p is peak discharge in cubic feet per second (cfs) and the conversion factor 645.33 is the rate required to discharge one inch from one square mile in one hour.

The relationship of the triangular unit hydrograph, $T_r = 1.67\ T_p$, gives K = 0.75. Then substituting into equation 16.5 gives:

$$q_p = \frac{484\ A\ Q}{T_p} \qquad \text{(Eq. 16.6)}$$

Since the volume under the rising side of the triangular unit hydrograph is equal to the volume under the rising side of the curvilinear dimensionless unit hydrograph in figure 16.2, the constant 484, or peak rate factor, is valid for the dimensionless unit hydrograph in figure 16.1.

Any change in the dimensionless unit hydrograph reflecting a change in the percent of volume under the rising side would cause a corresponding change in the shape factor associated with the triangular hydrograph and therefore a change in the constant 484. This constant has been known to vary from about 600 in steep terrain to 300 in very flat swampy country. If for some reason it becomes necessary to vary the dimensionless shape of the hydrograph the ratio of the percent of total volume in the rising side of the unit hydrograph to the rising side of a triangle is a useful tool in arriving at the peak rate factor.

Figure 16.2 shows that:

$$T_p = \frac{D}{2} + L \qquad \text{(Eq. 16.7)}$$

where D is the duration of unit excess rainfall and L is the watershed lag in hours. The lag (L) of a watershed is defined as the time from the center of mass of excess rainfall (D) to the time to peak (T_p) of a unit hydrograph. From equation 16.6:

$$q_p = \frac{484\ A\ Q}{\frac{D}{2} + L} \qquad \text{(Eq. 16.8)}$$

The average relationship of lag (L) to time of concentration (T_c) is $L = 0.6\ T_c$ 1 1/

Substituting in equation 16.8, the peak rate equation becomes:

$$q_p = \frac{484\ A\ Q}{\frac{D}{2} + 0.6\ T_c} \qquad \text{(Eq. 16.9)}$$

The time of concentration is defined in two ways: (1) the time for runoff to travel from the furthermost point in the watershed to one point in question, and (2) the time from the end of excess rainfall to the point of inflection of the unit hydrograph.

These two relationships are important since T_c is computed under the first definition and D, the unit storm duration, is used to compute the time to peak (T_p) of the unit hydrograph. This in turn is applied to all of the points on the abscissa of the dimensionless unit hydrograph using the ratio t/T_p as shwon in table 16.1.

The dimensionless unit hydrograph shown in figure 16.2 has a time to peak at one unit of time and point of inflection at approximately 1.7 units of time. Using the relationships Lag = 0.6 T_c and the point of inflection = 1.7 T_c

Purpose: A time of concentration from which a lag time can be computed must be obtained for hydrograph construction representing runoff from a watershed. Various methods of estimating time of concentration, T_C, are as follows:

A. ESTIMATING T_c FROM STREAM HYDRAULICS (SCS GUIDE)

1. Obtain stream reaches and channel cross-sections from field surveys.
2. Find approximate channel bankfull discharge for each reach.
3. Compute average velocity for the bankfull discharge of each reach.
4. Use the average velocity and the valley length of the reach to compute travel time through each reach.
5. Add travel times of reaches to get T_C.

Note: Appendix B "Hydraulic Computations" presents methods of computing flows in natural channels.

B. ESTIMATING T_c FROM VELOCITY ESTIMATES AND WATERCOURSE LENGTHS

Velocity Estimate Guide

U.S. Navy - Technical Publication Navdocks TP-PW-5 Table 8B, March 1953

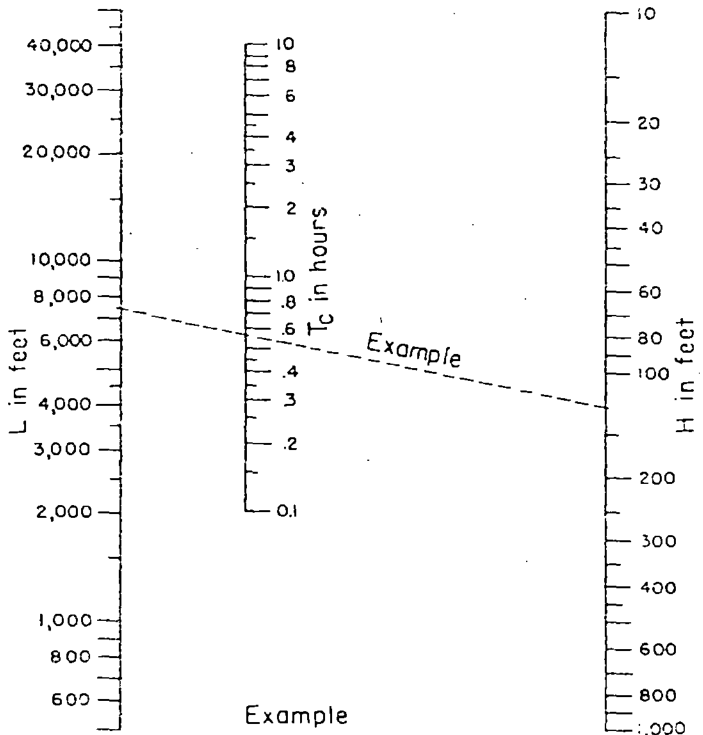
Average slope of channel from farthest point to outlet, in percent	Average velocity, feet per second
1 to 2	2.0
2 to 4	3.0
4 to 6	4.0
6 to 10	5.0

Texas Highway Department Rational Design of Culverts and Bridges, October 1946

Slope in percent	Average velocity, feet per second		
	Woodlands (upper portion watershed)	Pastures (upper portion watershed)	Natural channel not well defined
0 - 3	1.0	1.5	1.0
4 - 7	2.0	3.0	3.0
8 - 11	3.0	4.0	5.0
12 - 15	3.5	4.5	8.0

Figure 30. Time of concentration estimates. (Sheet 1 of 2.) 288-D-2461.

C. ESTIMATING T_c FROM LENGTHS AND SLOPES:



Example
L = 7,250 feet
H = 130 feet
then T_c = 0.57 hours

(a) Nomograph (SCS Guide)

L = length of longest watercourse in feet
H = difference in elevation in feet between outlet point and divide

(b) Solution may be made by equation from California Culverts Practice, California Highways and Public Works, September 1942.

$$T = \left(\frac{11.9\,L^3}{H}\right)^{0.385}$$

T = T_c in hours
L = length of longest watercourse in miles
H = elevation difference in feet

Lag, L, (SCS Guide) may be estimated directly for a basin by subdividing into tributary drainage subareas and using the relationship:

$$L = \frac{\Sigma a_x T_x}{A}$$, where L = lag in hours
a_x = the x-th increment of area in sq. mi.
T_x = travel time in hours from center of a_x to main basin outlet
A = total area of basin, sq. mi.

Figure 30. Time of concentration estimates. (Sheet 2 of 2.) 288-D-2462.

APPLICATION OF UNIT HYDROGRAPH

The unit hydrograph can be constructed for any location on a uniformly shaped watershed, once the values of q_p and T_p are defined (figure 16.3, areas A and B).

Area C in figure 16.3 is an irregularly shaped watershed having two uniformly shaped areas (C2 and C1) with a big difference in their time of concentration. This watershed requires the development of two unit hydrographs which may be added together forming one irregularly shaped unit hydrograph. This irregularly shaped unit hydrograph may be used to develop a flood hydrograph in the same way as the unit hydrograph developed from the dimensionless form (figure 16.1) is used to develop the flood hydrograph. See example 1 for area shown in figure 16.3. Also, each of the two unit hydrographs developed for areas C2 and C1 in figure 16.3 may be used to develop a flood hydrograph for its respective C2 and C1 areas. The flood hydrographs from each area are then combined to form the hydrograph at the outlet of area C.

There are many variables integrated into the shape of a unit hydrograph. Since a dimensionless unit hydrograph is used and the only parameters readily availble from field data are drainage area and time of concentration, consideration should be given to dividing the watershed into hydrologic units of uniformly shaped areas. These divisions, if at all possible, should be no greater than 20 square miles in area and should have a homogeneous drainage pattern.

The "storm duration" is the actual time duration of precipitation excess. This time duration varies with actual storms and <u>should not be confused with the unit time or unit hydrograph duration.</u>

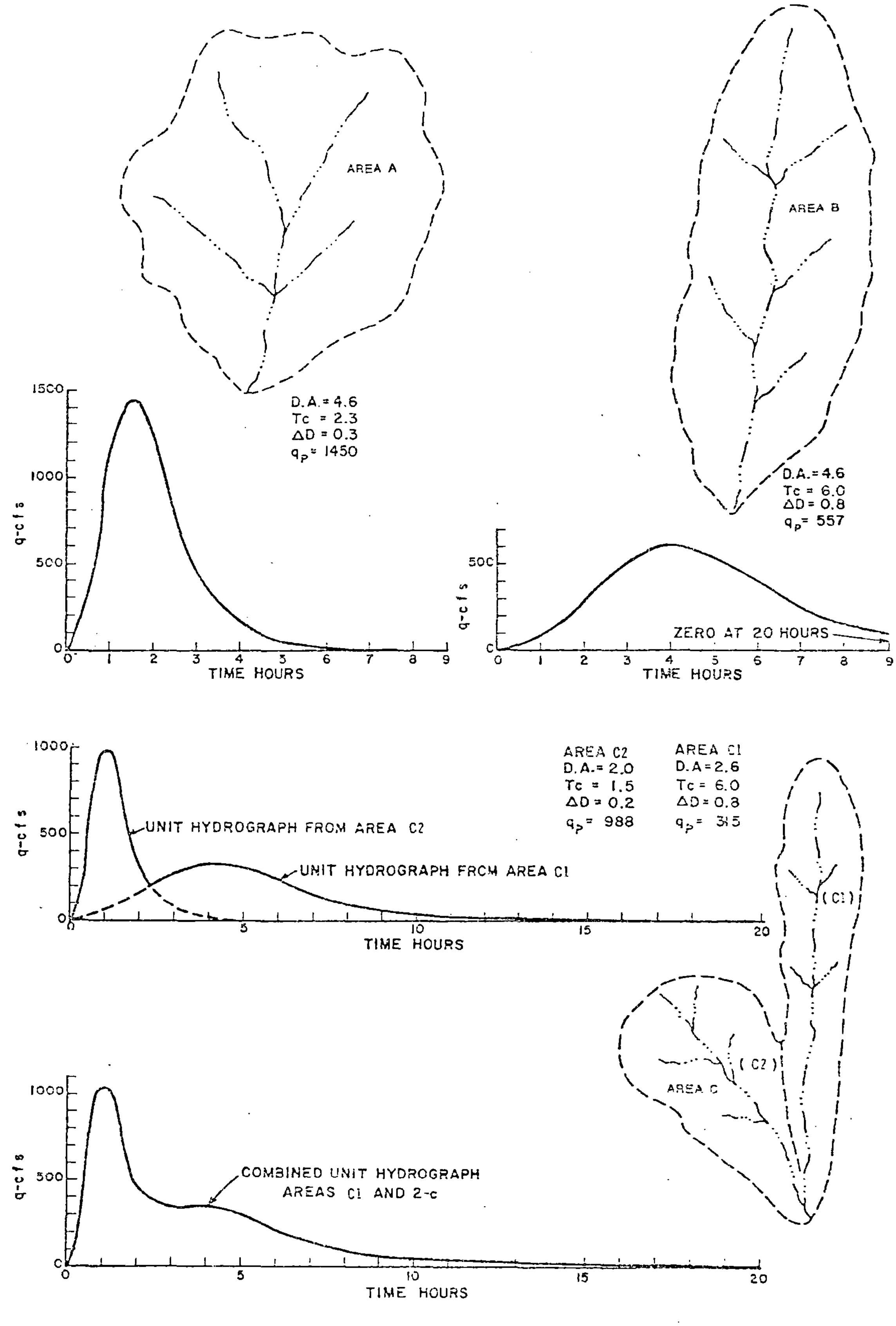


Figure 16.3 The effect of watershed shape on the peaks of unit hydrographs

STORAGE ROUTING

The SCS hydrograph procedures are designed for use in simulating runoff from rainfall. Where virtually all of the streamflow is generated from snowmelt, or moderate to low intensity general rainfall, these methods must be modified to account for the substantial component of subsurface flow. It is reiterated here that in general, rainfall (except moderate to high-intensity rainfall) and snowmelt reaches the stream channel as subsurface, rather than strictly surface runoff. Accordingly, routing procedures must take this "hydrologic axiom" into consideration.

Another method of generating the hydrograph is to assume that the watershed is analogous to one or more nonlinear storage reservoirs. Hence, the method of routing water available for streamflow (generated runoff) is based on the law of continuity in the storage equation:

$$S_1 + I - \frac{Q_1 + Q_2}{2} = S_2 \qquad (1)$$

where S_1 = storage on the watershed at the beginning of a time interval (1 day)

I = input (generated runoff) during the interval,

Q_1 = outflow at the beginning of an interval,

Q_2 = outflow at the end of the interval, and

S_2 = storage at the end of the interval.

All of the variables in equation (1) are in inches.

In performing the routing computation, the computer obtains simultaneous solutions for equation (1) and the basin storage-discharge relationship. An index of storage is obtained from a

volume-versus-flow curve development for a given watershed which relates discharge to the remaining runoff volume beneath the average recession curve. Figure 1 is an example of a curve developed for a subalpine watershed in the Fraser Experimental Forest.

Storage on a watershed is expressed by the equation:

$$Q = a + b_1S + b_2S^2 + b_3S^3 + \ldots. \tag{2}$$

Rewriting (1),

$$(S_1 - \frac{Q_1}{2} + I = (S_2 + \frac{Q_2}{2}) \tag{3}$$

and combining equations (2) and (3) results in the expression:

$$(S - \frac{Q_1}{2} + I = S_2 + \frac{1}{2}(a+b_1S_2 + b_3S_2^{\,2} + \ldots) \tag{4}$$

from which S_2 can be determined, given the initial conditions S_1 and Q_i and the input during the interval. Substitution of S_2 into equation (3) yields the discharge at the end of the interval, Q_2. Figure 2 is a simplified flow chart of the computational procedure.

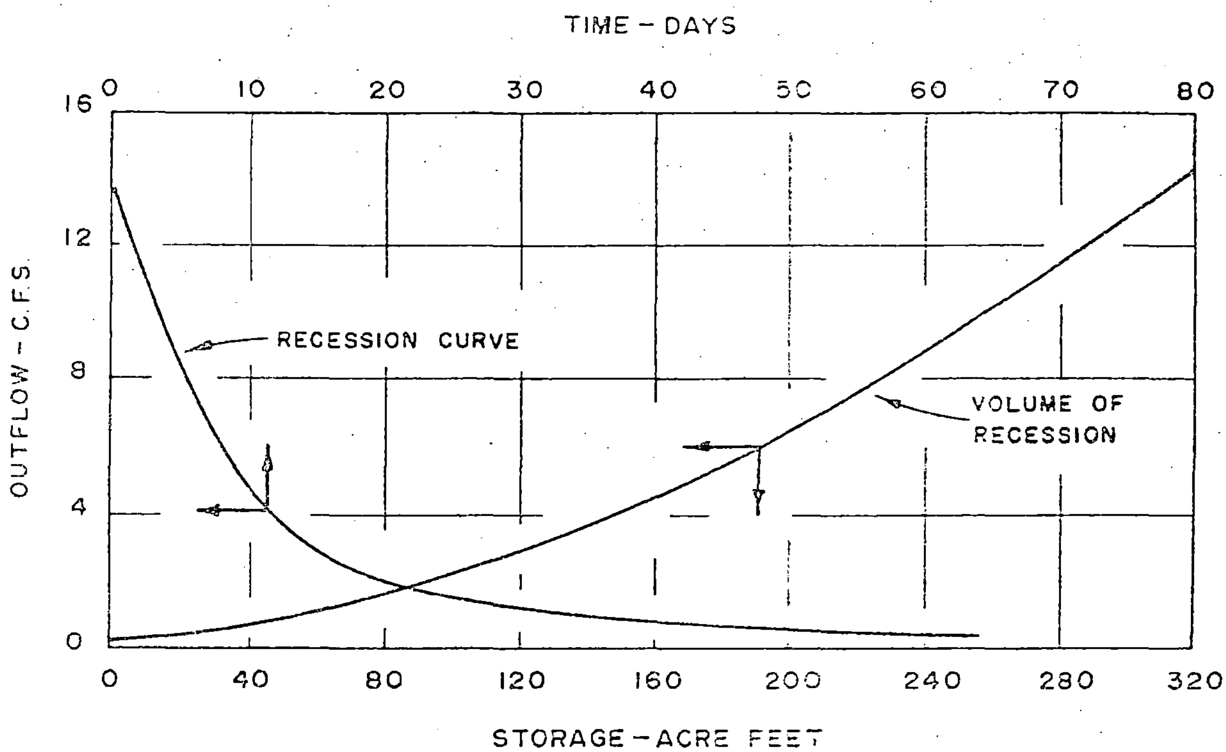


Figure 1.--Recession and outflow-storage curves for subalpine watershed.

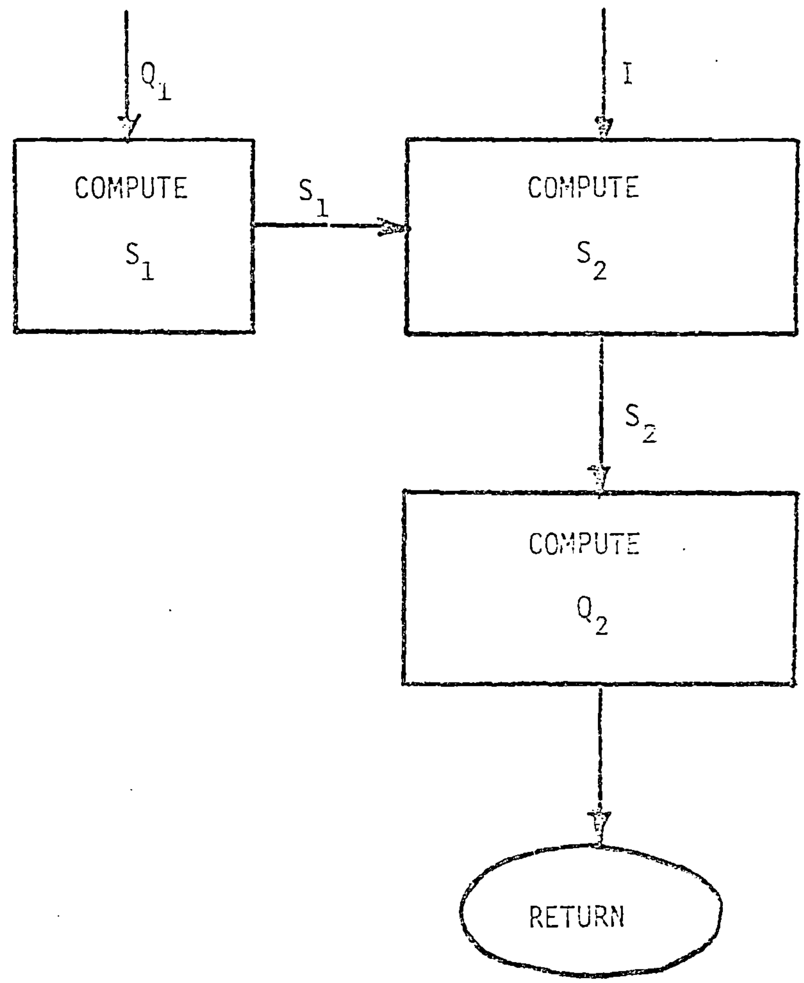
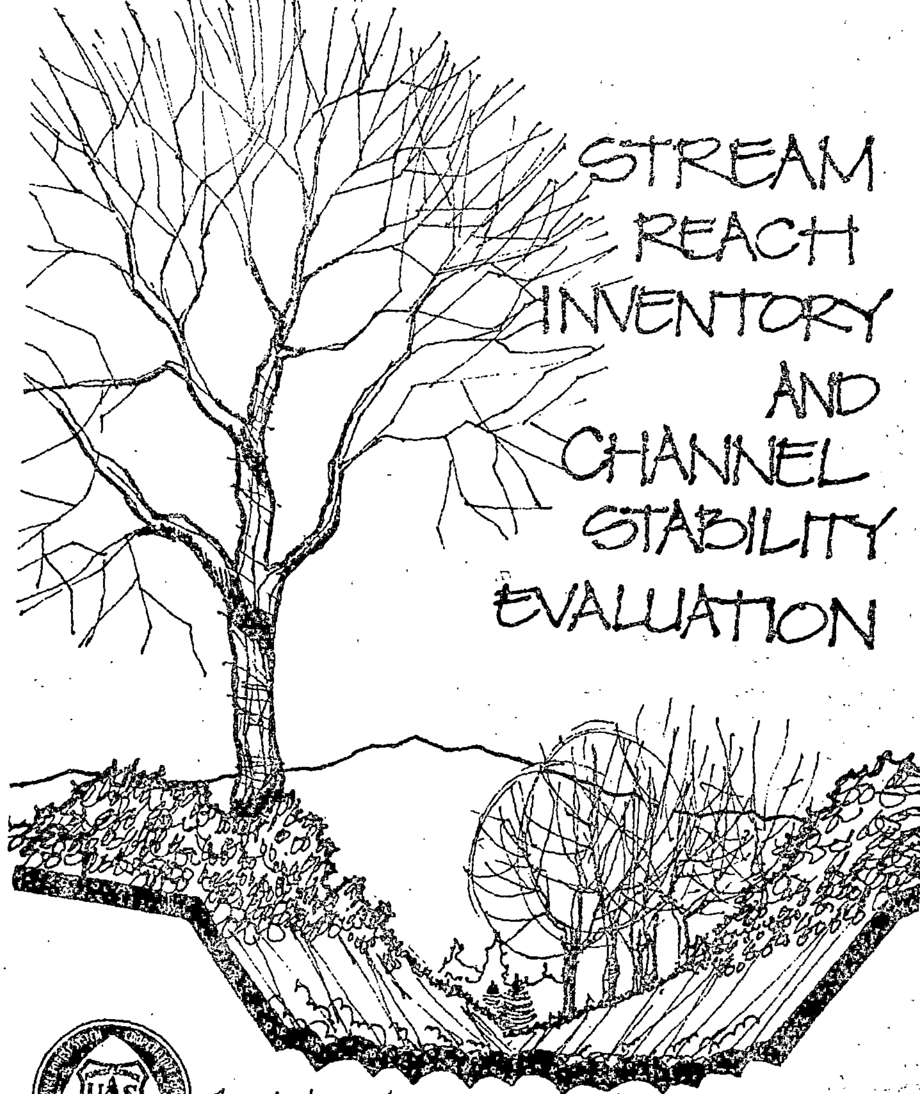


Figure 2.--Simplified storage routing procedure.

APPENDIX III

USFS CHANNEL RATING PROCEDURE

STREAM REACH INVENTORY AND CHANNEL STABILITY EVALUATION



A Watershed Management Procedure

U.S. Department of Agriculture
Forest Service/Northern Region

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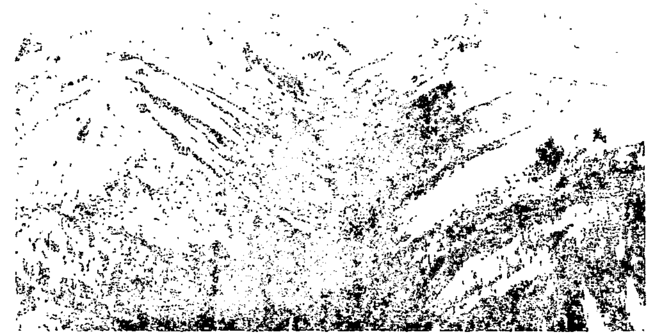
ACKNOWLEDGEMENTS



Playfair's Law: "Every river appears to consist of a main trunk, fed from a variety of branches, each running in a valley proportioned to its size, and all of them together forming a system of valleys connecting with one another, and having such a nice adjustment of their declivities that none of them join the principal valley either on too high or too low a level; a circumstance which would be infinitely improbable if each of these valleys were not the work of the stream which flows in it."

John Playfair, 1802

Others have built on John Playfair's observations. So it is with this work. Dr. Walter Megahan's original efforts at stream channel characterization in Utah a decade ago served as the stimulus. From that beginning the present system has evolved as a team effort. It has been my pleasure to shephard this work and contribute from my personal experience and observations. My Northern Region colleagues, past and present, have contributed so much in the way of suggestions and critique that it is impossible now to say "this is his and this is mine". My thanks and appreciation go especially to Dave Rosgen and Lee Silvey who labored through several revisions of the field form with me. Now the ball passes to you. Take it and run!

Dale J. Pfankuch, Forester
Lolo National Forest
Missoula, MT
March 17, 1975

STREAM REACH INVENTORY AND CHANNEL STABILITY EVALUATION

Channel evaluations are best made during periods of low flow.

Purpose: These procedures were developed to systemize measurements and evaluations of the resistive capacity of mountain stream channels to the detachment of bed and bank materials and to provide information about the capacity of streams to adjust and recover from potential changes in flow and/or increases in sediment production.

Uses: The information may be gathered at a "point" for projects such as bridge sites, campground, etc., or in complete channel analyses for fisheries, timber management water balance or multiple use inventories and planning. Stream reaches may be stratified by order and geologic type and sampled to an intensity that meets survey requirements. "Point" as used here always means a reach of sufficient length to provide the observer with a range of information on which to base a sound selection from available alternattives.

Instructions: The card format of R-1 Form 2500-5A and this pocket field guidebook are designed to be used together - in the field. Use a separate rating card for each length of stream that appears similar. Identify the reach on Card Form 2500-5A, on maps and/or photos in sufficient detail so others can locate the same reach at some future time.

The inventory items are completed using maps, aerial photos and field observations and measurements. Circle all estimated data items that could be measured but weren't. The precision of measurements will be dictated by the requirements of the particular inventory. These standards should be clearly in mind when the work begins.

The evaluation portion of the inventory requires judgement based on experience and the criteria outlined in this booklet. The condition descriptions, briefly explained on the tally form, are amplified in more detail in the pages that follow. As you begin the evaluation phase of the inventory, a few words of caution are in order. Avoid keying in on a single indicator or a small group of indicators in making ratings. Since the indicators are interrelated, don't dwell on any one item for long. If all are used without bias, the maximum diagnostic value can be obtained. Do the best you can. Experience has shown that over and underratings tend to balance out. Total rating scores made by inexperienced persons are often numerically close to the scores of those with more experience.

Keep in mind that each item directly or indirectly is designed to answer three basic questions:

1. What are the magnitudes of the hydraulic forces at work to detach and transport the various organic and inorganic bank and channel components?

2. How resistent are these components to the recent stream flow forces exerted on them?

3. What is the capacity of the stream to adjust and recover from potential changes in flow volume and/or increases in sediment production?

The channel and adjacent flood plain banks are subjectively rated, item by item, following an on-the-ground inspection. Circle only one of the numbers in parentheses for each item rated. If actual conditions fall somewhere between the conditions as described, cross out the number given and below it write in an intermediate value which better expresses the situation as you see it.

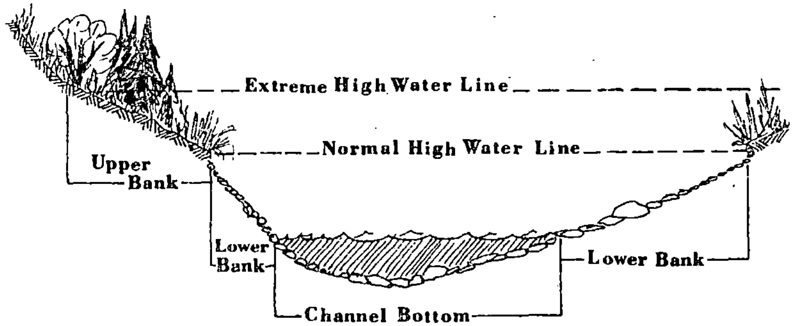
NOTE: Channels cut to bedrock are always rated Excellent.

DEFINITION OF TERMS AND ILLUSTRATIONS

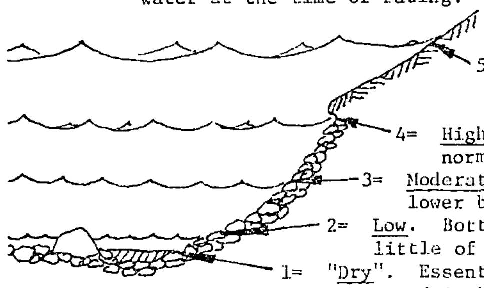
Upper Bank - That portion of the topographic cross section from the break in the general slope of the surrounding land to the normal high water line. Terrestrial plants and animals normally inhabit this area.

Lower Banks - The intermittently submerged portion of the channel cross section from the normal high water line to the water's edge during the summer low flow period.

Channel Bottom - The submerged portion of the channel cross section which is totally an aquatic environment.



Stream Stage - The height of water in the channel at the time of rating is recorded, using numbers 1 through 5. These numbers, as shown below, relate to the surface water elevation relative to the normal high water line. A decimal division should be used to more precisely define conditions, i.e., 3.5 means 3/4ths of the channel banks are under water at the time of rating.



5= Flooding. The flood plain is completely covered.

4= High. Channel full to the normal high water line.

3= Moderate. Bottom and 1/2 of lower banks wetted.

2= Low. Bottom covered but very little of the lower banks wet.

1= "Dry". Essentially no flow. Water may stand in bottom depressions.

KEY CARD FOR FIELD FORM 2500-5A

KEY NUMBER ON FIELD CARDS

	Item Rated	
Upper Banks	Landform Slope	1
	Mass Wasting or Failure (existing or potential)	2
	Debris Jam Potential (Floatable Objects)	3
	Vegetative Bank Protection	4
Lower Banks	Channel Capacity	5
	Bank Rock Content	6
	Obstructions Flow Deflectors Sediment Traps	7
	Cutting	8
	Deposition	9
Bottom	Rock Angularity	10
	Brightness	11
	Consolidation or Particle Packing	12
	Bottom Size Distribution and Percent Stable Materials	13
	Scouring and Deposition	14
	Clinging Aquatic Vegetation (Moss and Algae)	15

R-1 STREAM REACH INVENTORY and CHANNEL STABILITY EVALUATION

REACH LOCATION: Survey Date 8-12-75 Time 1430 Obs. D.R. - L.S. - D.P.

Forest Brightwater Rgr. Dist. Purity

Stream Fern Creek P.W.I. W/S No. 16-02-00-04-23-05-01-01

Reach Description & Other Identification Road crossing Sec 3 to 1/4 mi. upstream Aerial Photo #274-191

	Key #	Stability Indicators by Classes EXCELLENT		(Fair and Poor on reverse side) GOOD	
Upper Banks	1	Bank slope gradient <30%.	(2)	Bank slope gradient 30-40%.	(4)
	2	No evidence of past or any potential for future mass wasting into channel.	3	Infrequent and/or very small. Mostly healed over. Low future potential.	(6)
	3	Essentially absent from immediate channel area.	(2)	Present but mostly small twigs and limbs.	4
	4	90%+ plant density. Vigor and variety suggests a deep, dense, soil binding, root mass.	3	70-90% density. Fewer plant species or lower vigor suggests a less dense or deep root mass.	(6)
Lower Banks	5	Ample for present plus some increases. Peak flows contained. W/D ratio <7.	(1)	Adequate. Overbank flows rare. Width to Depth (W/D) ratio 8 to 15.	2
	6	65%+ with large, angular boulders 12"+ numerous.	(2)	40 to 65%, mostly small boulders to cobbles 6-12".	4
	7	Rocks and old logs firmly embedded. Flow pattern without cutting or deposition. Pools and riffles stable.	2	Some present, causing erosive cross currents and minor pool filling. Obstructions and deflectors newer and less firm.	(4)
	8	Little or none evident. Infrequent raw banks less than 6" high generally.	(4)	Some, intermittently at outcurves and constrictions. Raw banks may be up to 12".	6
	9	Little or no enlargement of channel or point bars.	4	Some new increase in bar formation, mostly from coarse gravels.	(8)
Bottom	10	Sharp edges and corners, plane surfaces roughened.	(1)	Rounded corners and edges, surfaces smooth and flat.	2
	11	Surfaces dull, darkened, or stained. Gen. not "bright".	(1)	Mostly dull, but may have up to 35% bright surfaces.	2
	12	Assorted sizes tightly packed and/or overlapping.	2	Moderately packed with some overlapping.	(4)
	13	No change in sizes evident. Stable materials 80-100%.	4	Distribution shift slight. Stable materials 50-80%.	(8)
	14	Less than 5% of the bottom affected by scouring and deposition.	6	5-30% affected. Scour at constrictions and where grades steepen. Some deposition in pools.	(12)
	15	Abundant. Growth largely moss-like, dark green, perennial. In swift water too.	(1)	Common. Algal forms in low velocity & pool areas. Moss here too and swifter waters.	2
		EXCELLENT COLUMN TOTAL →	24	GOOD COLUMN TOTAL →	22

Add values in each column and record in spaces below. Add column scores.

E. 24 + G. 22 + F. 6 + P. 0 = 52 Total Reach Score.

Adjective ratings: <38=Excellent, 39-76=Good, 77-114=Fair, 115+=Poor*

*(Scores above may be locally adjusted by Forest Hydrologist)

R1-Form 2500-5A Rev.1-75 Side 1.

INVENTORY DATA: (observed or measured on this date) Side 2

Stream Width 6 ft. X Ave. Depth 0.5 ft. X Ave. Velocity 1.2 /s = 3.6 Flow cfs
Reach Gradient 4 %, Stream Order 3, Turbidity Level Low, Stream Stage Low (2.3), Sinuosity Ratio 1.2.
Temperature °F or °C of: Air 86 Water 52, Others pH 7.2, Conductance 45 μMhos
Water Quality Sample Bottle # 34

	Key #	Stability Indicators by Classes FAIR		POOR	
Upper Banks	1	Bank slope gradient 40-60%.	(6)	Bank slope gradient 60%+.	(8)
	2	Moderate frequency & size, with some raw spots eroded by water during high flows.	(9)	Frequent or large, causing sediment nearly yearlong OR imminent danger of same.	(12)
	3	Present, volume and size are both increasing.	(6)	Moderate to heavy amounts, predominantly larger sizes.	(8)
	4	50-70% density. Lower vigor and still fewer species form a somewhat shallow and discontinuous root mass.	(9)	<50% density plus fewer species & less vigor indicate poor, discontinuous, and shallow root mass.	(12)
Lower Banks	5	Barely contains present peaks. Occassional overbank floods. W/D ratio 15 to 25.	(3)	Inadequate. Overbank flows common. W/D ratio > 25.	(4)
	6	20 to 40%, with most in the 3-6" diameter class.	(6)	<20% rock fragments of gravel sizes, 1-3" or less.	(8)
	7	Moderately frequent, moderately unstable obstructions & deflectors move with high water causing bank cutting and filling of pools.	(6)	Frequent obstructions and deflectors cause bank erosion yearlong. Sediment traps full, channel migration occurring.	(8)
	8	Significant. Cuts 12"-24" high. Root mat overhangs and sloughing evident.	(12)	Almost continuous cuts, some over 24" high. Failure of overhangs frequent.	(16)
	9	Moderate deposition of new gravel & coarse sand on old and some new bars.	(12)	Extensive deposits of predominantly fine particles. Accelerated bar development.	(16)
Bottom	10	Corners & edges well rounded in two dimensions.	(3)	Well rounded in all dimensions, surfaces smooth.	(4)
	11	Mixture, 50-50% dull and bright, ± 15% ie. 35-65%.	(3)	Predominantely bright, 65%+, exposed or scoured surfaces.	(4)
	12	Mostly a loose assortment with no apparent overlap.	(6)	No packing evident. Loose assortment, easily moved.	(8)
	13	Moderate change in sizes. Stable materials 20-50%.	(12)	Marked distribution change. Stable materials 0-20%.	(16)
	14	30-50% affected. Deposits & scour at obstructions, constrictions, and bends. Some filling of pools.	(18)	More than 50% of the bottom in a state of flux or change nearly yearlong.	(24)
	15	Present but spotty, mostly in backwater areas. Seasonal blooms make rocks slick.	(3)	Perennial types scarce or absent. Yellow-green, short term bloom may be present.	(4)
		FAIR COLUMN TOTAL →	6	POOR COLUMN TOTAL →	0

Size Composition of Bottom Materials (Total to 100%)

1. Exposed bedrock........... 0 %	5. Small rubble, 3"-6"..... 30 %
2. Large boulders, 3'+ Dia.... 5 %	6. Coarse gravel, 1"-3".... 25 %
3. Small boulders, 1-3'....... 10 %	7. Fine gravel, 0.1-1"..... 20 %
4. Large rubble, 6"-12"....... 10 %	8. Sand, silt, clay, muck.. T %

Amplification of the Stream Channel Evaluation Items

General

Space on the field form permits only the very briefest description of the various components. This field booklet provides, in the text which follows, some of the basic rationale in support of these brief "kernels" or core thoughts. These explanations are arranged in the same order as they appear on the field form.

The channel cross section is subdivided into three components, to focus your attention on the various indicators to be subjectively evaluated. Once again, you are cautioned not to "key in" on any one item or group of items. All that have been included are interralated and all must be used in an unbiased way to achieve consistent evaluations of the current situation.

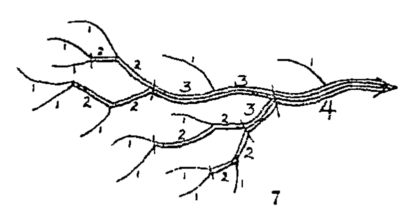
Stream channel ratings should not be attempted without the preparation provided by this Field Guide. The language of the text has been kept rather general to avoid limiting its use as a management tool to a small geographic area. These general descriptions, coupled with your local experience, will stimulate mental images of indicator conditions which, when shared with fellow workers, will lead to consistent, reproducible ratings.

Illustrations in the text should be considered general in nature and not specific for all situations. It is suggested that local conditions be photographed and the pictures added to this Field Guide to achieve local uniformity.

A word of additional caution: Keep the scale of the reach being evaluated in context with the scale of dimensions given in the text and on the inventory form. Rating items were taylored for and best fit the 2nd to 4th order stream reaches. Very small, unbranched, first order segments will require a scaling down of sizes while the larger stream and river reaches will require some mental enlargement of the criteria given to fit the situation.

STREAM ORDER CLASSIFICATION

First order streams are unbranched reaches found usually but not exclusively at the head of drainage basins. Second order reaches are formed when two or more first order reaches come together and so on as illustrated below.



I. Upper Channel Banks

The land area immediately adjacent to the stream channel is normally and typically a terrestrial environment. Landforms vary from wide, flat, alluvial flood plains to the narrow, steep termini of mountain slopes. Intermittently this dry land flood plain becomes a part of the water course. Forces of velocity and turbulence tear at the vegetation and land. These hydrologic forces, while relatively short lived, have great potential for producing onsite enlargements of the stream channel and downstream sedimentation damage. Resistance of the component elements on and in the bank are highly variable. This section is designed to aid in rating this relative resistence to detachment and transport by floods.

A. Landform Slope: The steepness of the land adjacent to the stream channel determines the lateral extent and ease to which banks can be eroded and the potential volume of slough which can enter the water. All other factors being equal, the steeper the land adjacent to the stream, the greater the potential volume of slough materials.

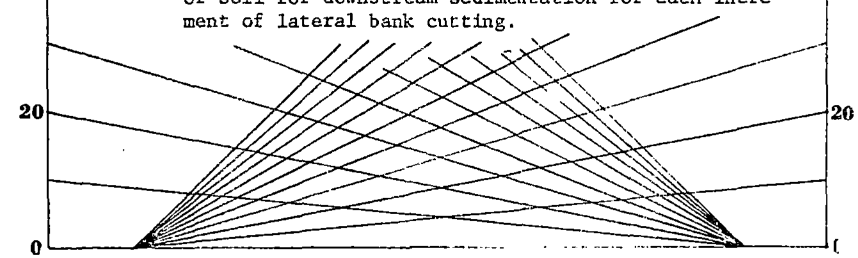
The 60% limit for poor was selected as a conservative gravitational repose angle for unconsolidated soil materials. Slopes steeper than this are rated poor because they would erode into the stream by gravity alone, if denuded of their protecting vegetation. The other ratings built on this limit and are arbitrarily set as follows:

1. Excellent: Side slopes to the channel are generally less than 30 percent on both banks.

2. Good: Side slopes up to 40% on one or occasionally both banks.

3. Fair: Side slopes to 60% common on one or both banks.

4. Poor: Steep slopes, over 60%, provide larger volumes of soil for downstream sedimentation for each increment of lateral bank cutting.



PERCENT SLOPE SCALE

Hold this page at arms length..match the slope of the topography with the percent slope lines on the scale above.

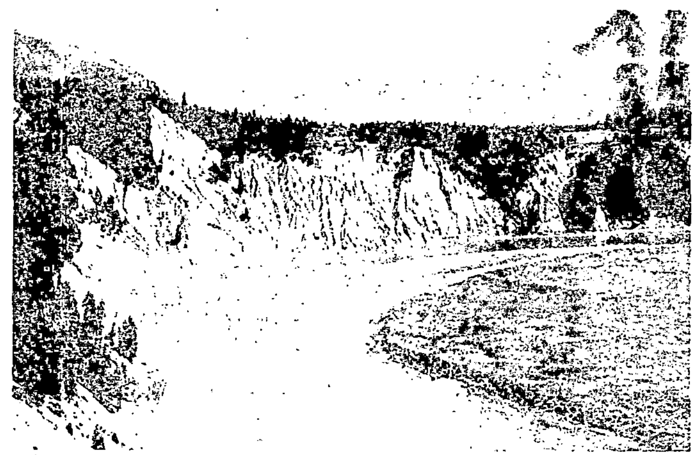
B. Mass Wasting Hazard This rating involves existing or potential detachment from the soil mantle and downslope movement into waterways of relatively large pieces of ground. Mass movement of banks by slumping or sliding introduces large volumes of soil and debris into the channel suddenly, causing constrictions or complete damming followed by increased stream flow velocities, cutting power and sedimentation rates. Conditions deteriorate in this element with proximity, frequency and size of the mass wasting areas and with progressively poorer internal drainage and steeper terrain:

1. Excellent: There is no evidence of mass wasting that has or could reach the stream channel.

2. Good: There is evidence of infrequent and/or very small slumps. Those that exist may occasionally be "raw" but predominately the areas are revegetated and relatively stable.

3. Fair: Frequency and/or magnitude of the mass wasting situation increases to the point where normal high water aggrevates the problem of channel changes and subsequent undercutting of unstable areas with increased sedimentation.

4. Poor: Mass wasting is not difficult to detect because of the frequency and/or size of existing problem areas or the proximity of banks are so close to potential sides that any increases in the flow would cut the toe and trigger slides of significant size to cause downstream water quality problems for a number of years.



Mass wasting of slopes directly into the stream channel.

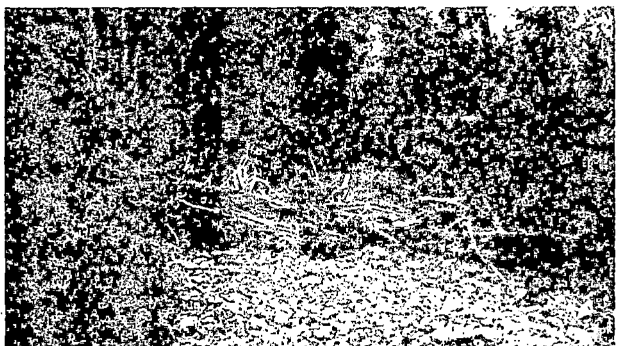
C. Debris Jam Potential Floatable objects are deposited on stream banks by man and as a natural process of forest ecology. By far, the bulk of this debris is natural in origin. Tree trunks, limbs, twigs, and leaves reaching the channel form the bulk of the obstructions, flow deflectors, and sediment traps to be rated below. This inventory item assess the potential for increasing these impediments to the natural direction and force of flow where they now lay. It also includes the possibility of creating new debris jams under certain flow conditions.

1. Excellent: Debris may be present on the banks, but is so situated or is of such a size, that the stream is not able to push or float it into the channel and, therefore, for all intents and purposes, it is absent. In truth, there may be none physically present. Both situations are rated the same.

2. Good: The debris present offers some bank protection for a while but is small enough to be floated away in time. Only small jams could be formed with this material alone.

3. Fair: There is a noticeable accumulation of all sizes and the stream is large enough to float it away, at certain times, thus decreasing the bank protection and adding to the debris jam potential downstream.

4. Poor: Moderate to heavy accumulations are present due to fires, insect attack, disease mortality, windthrow, or logging slash. High flows will float some debris away and the remainder will cause channel changes.



A series of debris jams of small size materials like the one shown in the center of this photo cause this item to be rated "Poor".

D. Vegetative Bank Protection: The soil in banks is held in place largely by plant roots. Riparian plants have almost unlimited water for both crown and root development. Their root mats generally increase in density with proximity to the open channel. Trees and shrubs generally have deeper root systems than grasses and forbs. Roots seldom extend far into the water table, however, and near the shore of lakes and streams they may be comparatively shallow rooted. Some species are, therefore, subject to windthrow.

In addition to the benefits of the root mat in stabilizing the banks, the stems help to reduce the velocity of flood flows. Turbulence is generated by stems in what may have been laminar flow. The seriousness of this energy release depends on the density of both overstory and understory vegetation. The greater the density of both, the more resistence displayed. Damage from turbulence is greatest at the periphery and diminishes with distance from the normal channel. Other factors to consider, in addition to the density of stems, are the varieties of vegetation, the vigor of growth and the reproduction processes. Vegetal variety is more desirable than a monotypic plant community. Young plants, growing and reproducing vigorously, are better than old, decadent stands.

1. Excellent: Trees, shrubs, grass and forbs combined cover more than 90 percent of the ground. Openings in this nearly complete cover are small and evenly dispersed. A variety of species and age classes are represented. Growth is vigorous and reproduction of species in both the under- and over-story is proceeding at a rate to insure continued ground cover conditions. A deep, dense root mat is inferred.
2. Good: Plants cover 70 to 90 percent of the ground. Shrub species are more prevalent than trees. Openings in the tree canopy are larger than the space resulting from the loss of a single mature individual. While the growth vigor is generally good for all species, advanced reproduction may be sparse or lacking entirely. A deep root mat is not continuous and more serious erosive incursions are possible in the openings.
3. Fair: Plant cover ranges from 50 to 70 percent. Lack of vigor is evident in some individuals and/or species. Seedling reproduction is nil. This condition ranked fair, based mostly on the percent of the area not covered by vegetation with a deep root mat potential and less on the kind of plants that make up the overstory.
4. Poor: Less than 50 percent of the ground is covered. Trees are essentially absent. Shrubs largely exist in scattered clumps. Growth and reproduction vigor is generally poor. Root mats discontinuous and shallow.

II. Lower Channel Banks

The channel zone is located between the normal high water and low water lines. Both aquatic and terrestrial plants may grow here but normally their density is sparse.

The lower channel banks define the present stream width. Stability of these channel banks is indicated under a given flow regimen by minor and almost imperceptable changes in channel width from year to year. In other words, encroachment of the water environment into the land environment is nil.

Under conditions of increasing channel flow, the banks may weaken and both cutting (bank encroachment) and deposition (bank extension) begin, usually at bends and points of constriction. Cutting is evidenced by steepening of the lower banks. Eventually the banks are undercut, followed by cracking and slumping. Deposition behind rocks or bank protrusions increase in length and depth.

As the channel is widened, it may also be deepened to accomodate the increased volume of flow. For convenience only, changes of channel bottoms are observed separately and last in this evaluation scheme.

A. Channel Capacity: Channel width, depth, gradient, and roughness determine the volume of water which can be transmitted. Over time channel capacity has adjusted to the size of watershed above the reach rated, to climate, and to changes of vegetation. Some indicators of change are widening and/or deepening of the channel which affects the ratio of width to depth. When the capacity is exceeded, deposits of soil are found on the banks and organic debris may be found hung up in the bank vegetation. These are expressions of the most recent flood event. Indicators of conditions as recent as a year or two ago may be difficult or impossible to find, but do your best to estimate what normal peak flows are and whether the present cross section is adequate to handle the load without bank deterioration.

1. Excellent: Cross sectional area is ample for present peak volumes plus some additional, if needed. Overbank floods are rare. Width to depth ratio less than 7; i.e., (36' wide ÷ 6' deep = 6).

2. Good: Adequate cross sectional area contains most peak flows. Width to depth ratio 8 to 15.

3. Fair: Channel barely contains the peak runoff in average years or less. Width to depth ratios range from 15 to 25.

4. Poor: Channel capacity generally inadequate. Overbank floods quite common as indicated by kind and condition of the bank plants and the position and accumulation of debris. Width to depth ratio 25 or more.

B. Bank Rock Content: Examination of the materials that make up the channel bank will reveal the relative resistence of this component to detachment by flow forces. Since the banks are perennially and intermittently both aquatic and terrestrial environments, these sites are harsh for most plants that make up both types. Vegetation is, therefore, generally lacking and it is the volume, size and shape of the rock component which primarily determine the resistence to flow forces.

A soil pit need not be dug. Surface rock and exposed cut banks will enable you to categorize this item as listed by percentage ranges on the field form.

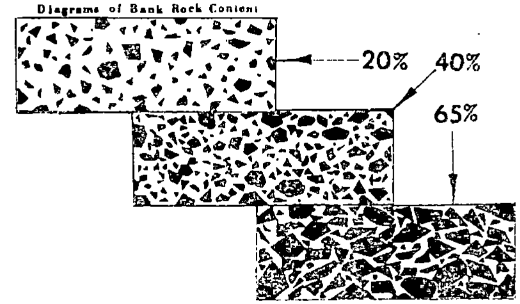
1. Excellent: Rock makes up 65% or more of the volume of the banks. Within this rock matrix large, angular boulders 12" (on their largest axis) are numerous.

2. Good: Banks 40-65% rock which are mostly small boulders and cobble ranging in size from 6-12" mean diameter. Some may be rounded while others are angular.

3. Fair: 20-40% of bank volume rock. While some big rock may be present, most fall into the 3-6" diameter class.

4. Poor: Less than 20% rock fragments, mostly of gravel sizes 1-3" in diameter.

Diagrams of Bank Rock Content



C. <u>Obstructions and Flow Deflectors</u>: Objects within the stream channel, like large rocks, embedded logs, bridge pilings, etc., change the direction of flow and sometimes the velocity as well. Obstructions may produce adverse stability effects when they increase the velocity and deflect the flow into unstable and unprotected banks and across unstable bottom materials. They also may produce favorable impacts when velocity is decreased by turbulence and pools are formed.

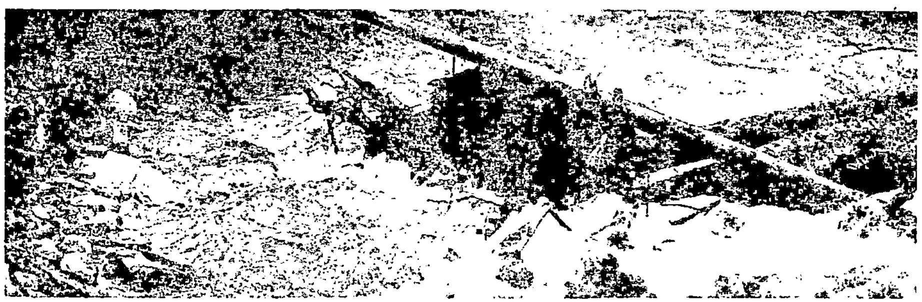
<u>Sediment Traps</u>: Channel obstructions which dam the flow partly or wholly form pools or slack water areas. The pools lower the channel gradient. With this loss of energy the sediment transport power is greately reduced. Coarse particles drop out first at the head of the pool. Some or all of the fine suspended particles may carry on through.

Embedded logs and large boulders can produce very stable natural dams which do not add to channel instability. Some debris dams and beaver dams, however, are quite unstable and only serve to increase the severity of channel damage when they break up.

The effectiveness of these sediment traps depends on pool length relative to entrance velocity. The swifter the current, the longer the pool needed to reach zero velocity. Turbulence caused by a falls at the head of the pool shortens the length required to reach zero velocity.

How long these traps are effective depends on depth and width as well as pool length and, of course, the rate of sediment accretion.

Items of vegetation growing in the water, like alders, willows, cattails, reeds, and sedges are also effective traps in some locations and reduce flow velocity and sediment carrying power.



Overturned shoreline trees become obstructions and flow deflectors as shown here. If frequent in the reach, rate this item "Poor".

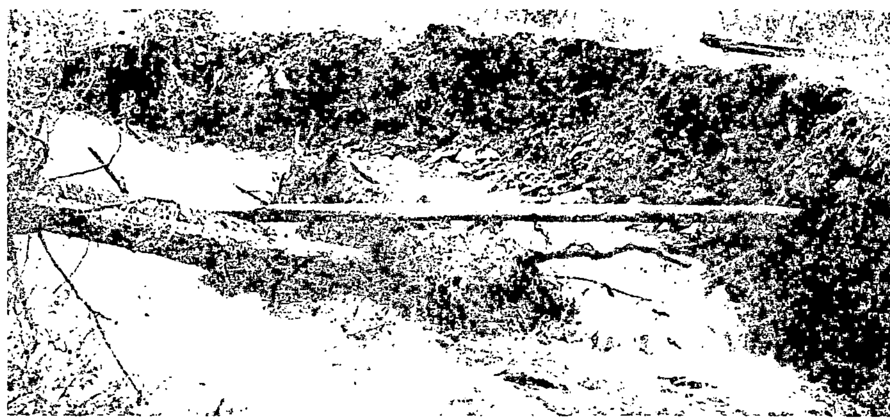
C. <u>Obstructions and Flow Deflectors</u> (Continued)

1. <u>Excellent</u>: Logs, rocks, and other obstructions to flow are firmly embedded and produce a pattern of flow which does not erode the banks and bottom or cause sediment buildups. Poolriffle relationship stable.

2. <u>Good</u>: Obstructions to flow and sediment traps are present, causing cross currents which create some minor bank and bottom erosion. Some of the obstructions are newer, not firmly embedded and move to new locations during high flows. Some sediment is trapped in pools decreasing their capacity.

3. <u>Fair</u>: Moderately frequent and quite often unstable obstructions, cause noticeable seasonal erosion of the channel. Considerable sediment accumulates behind obstructions.

4. <u>Poor</u>: Obstructions and traps so frequent they are intervisible, often unstable to movement and cause a continual shift of sediments at all seasons. Since traps are filled as soon as formed, the channel migrates and widens.



Same location as shown on page 14, but looking upstream. Obstruction like this could become the nucleus of a debris jam.

Cutting and Deposition are concommittent processes. You can't have one without the other. However, it is possible for each to be taking place in different reaches of the same stream at the same time, and hence the separation for classification purposes which follows.

D. Cutting: One of the first signs of channel degradation would be a loss of aquatic vegetation by scouring or uprooting. Some channels are naturally devoid of aquatic plants and here the first stages would be an increase in the steepness of the channel banks. Beginning near the top, and later extending in serious cases to the total depth, the lower channel bank becomes a near vertical wall.

If plant roots bind the surface horizon of the adjacent upper bank into a cohesive mass, undercutting will follow. This process continues until the weight of overhang causes the sod to crack and subsequently slump into the channel. Differential horizontal compaction and texture could also result in undercut banks even with an absence of vegetative cover. There are some loosely consolidated banks that with or without vegetation are literally nibbled away, never developing much, if any, overhang.

1. Excellent: Very little or no cutting is evident. Raw, eroding banks are infrequent, short and predominately less than 6" high.

2. Good: Some intermittent cutting along channel outcurves and at prominent constrictions. Eroded areas are equivalent in length to one channel width or less and the vertical cuts are predominately less than 12".

3. Fair: Significant bank cutting occurs frequently in the reach. Raw vertical banks 12" to 24" high are prevalent as are root mat overhangs and sloughing.

4. Poor: Nearly continuous bank cutting. Some reaches have vertical cut faces over 2 feet high. Undercutting, sod-root overhangs and vertical side failures may also be frequent in the rated reach.

Poor bank conditions at this bend are evident.

E. Deposition: Lower bank channel areas are generally the steeper portions of the wetted perimeter and may be rather narrow strips of land that offer slight opportunity for deposition. Exceptions to this statement abound since deposition is often noted on the lea side of large rocks and log deflectors which form natural jetties. However, these deposits tend to be short and narrow. On the less steep, lower banks, deposition during recession from peak flows can be quite large. The appearance of sand and gravel bars where they did not previously exist may be one of the first signs of upstream erosion. These bars tend to grow, primarily in depth and length, with continued watershed disturbance(s). Width changes are in a shoreward direction as overflow deposition takes place on the upper banks. Dimensional deposition "growth" is limited by the size and orientation of the obstructions to flow along the channel banks, flow velocity and a continuing upstream sediment supply.

Deposition may also occur on the inside radii of bends, particularly if active cutting is taking place on the opposite shore. Also, deposits are found below constrictions or where there is a sudden flattening of stream gradient as occurs upstream above geologic nic points.

1. Excellent: Very little or no deposition of fresh silt, sand or gravel in channel bars in straight reaches or point bars on the inside banks of curved reaches.

2. Good: Some fresh deposits on bars and behind obstructions. Sizes tend to be predominately from the larger size classes - coarse gravels.

3. Fair: Deposits of fresh, coarse sands and gravels observed with moderate frequency. Bars are enlarging and pools are filling so riffle areas predominate.

4. Poor: Extensive deposits of predominately fresh, fine sands, some silts, and small gravels. Accelerated bar development common. Storage areas are now full and sediments are moving even during low flow periods.

Poor conditions are illustrated here.

III. Channel Bottom

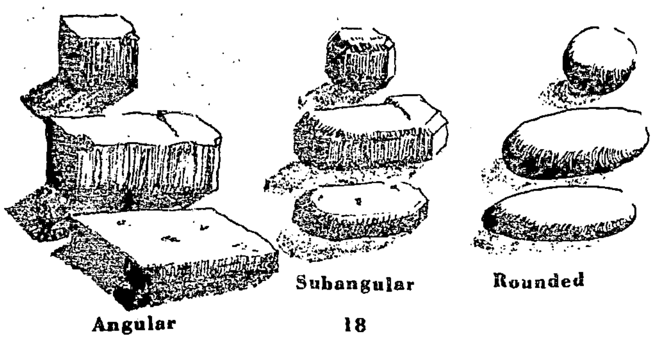
Water flows over the channel bottom nearly all of the time in perennial streams. It is, therefore, almost totally an aquatic environment, composed of inorganic rock constituents found in an infinite variety of kinds, shapes, and sizes. It is also a complex biological community of plant and animal life. This latter component is more difficult to discern and may in fact, at times and places, be totally lacking.

Both components, by their appearance alone and in combination, offer clues to the stability of the stream bottom. They are arbitrarily separated and individually rated for convenience and emphasis during the evaluation process. Because of the high reliance on the visual sense, inventory work is best accomplished during the low flow season and when the water is free of suspended or dissolved substances. If ratings must be made in high flow periods, sounds of movement may be the only clue as to the state of flux on the bottom.

A. Angularity: Rocks from stratified, metamorphic formations break out and work their way into channels as angular fragments that resist tumbling. Their sharp corners and edges wear and are rounded in time, but they resist the tumbling motion. These angular rocks pack together well and may orient themselves like shingles (imbricated). In this configuration they are resistant to detachment.

In contrast, igneous rocks often produce fragments that round up quickly, pack poorly and are easily detached and moved downstream.

Excellent to Poor ratings relate to the amount of rounding exhibited and, secondarily, the smoothness or polish the surfaces have achieved. Some rocks never do smooth up in the natural environment, but most round up in time. Both conditions, of course, are relative within the inherent capability of the respective rock types.



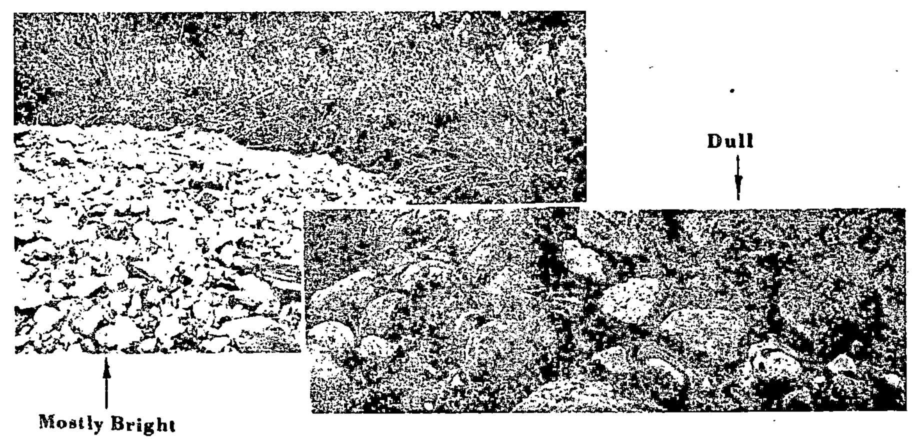
B. Brightness: Rocks in motion "gather no moss", algae or stain either. They become polished by frequent tumbling and, as a general rule, appear brighter in their chroma values than similar rocks which have remained stationary. The degree of staining and vegetative growths relate also to water temperature, seasons, nutrient levels, etc. In some areas a "bright" rock will be "dulled" in a matter of weeks or months. In another it may take years to achieve the same results. Nevertheless, even slight changes during the spring runoff should be detectable during the next summer's survey. Look first for changes in the sands and gravels.

1. Excellent: Less than 5% of the total bottom should be bright, newly polished and exposed surfaces. Most will be covered by growths or a film of organic stain. Stains may also be from minerals dissolved in the water.

2. Good: 5 to 35% of the bottom appears brighter, some of which may be on the larger rock sizes.

3. Fair: About a 50-50 mixture of bright and dull with a 15% leeway in either direction (i.e., a range of from 35 to 65% bright materials).

4. Poor: Bright, freshly exposed rock surfaces predominate with two-thirds or more of the bottom materials in motion recently.



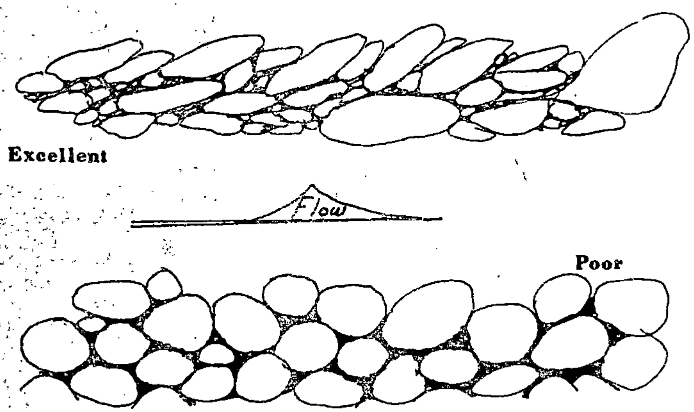
C. Consolidation (Particle Packing): Under stable conditions, the array of rock and soil particle sizes pack together. Voids are filled. Larger components tend to overlap like shingles (imbricate). So arranged, the bottom is quite resistent to even exceptional flow forces. Some rock types (granitics) are less amenable to this packing process and never reach the stable state of others like the Belt Series rocks.

1. Excellent: An array of sizes are tightly packed and wedged with much overlapping which makes it difficult to dislodge by kicking.

2. Good: Moderately tight packing of particles with fast water parts of the cross section protected by overlapping rocks. These might be dislodged by higher than average flow conditions, however.

3. Fair: Moderately loose without any pattern of overlapping. Most elements might be moved by average high flow conditions.

4. Poor: Rocks in loose array, moved easily by less than high flow conditions and move underfoot while walking across the bottom. The shape of these rocks tends to be predominantly round and sorted so that most are of similar size.



Side Views of Substrate

D. Bottom Size Distribution and Percent Stable Materials:

Rocks remaining on a stream's bottom reflect the geologic sources within the basin and the flow forces of the past. Normally, there is an array of sizes that you expect to see in any given local. After a little experience, you begin to "sense" abnormal situations. Generally, in the mature topography typical of the Northern Region of the Forest Service and much of the other western Regions as well, the flow in the small, steep upper stream reaches is sufficient to wash the soil separates and some of the gravels away. What remains is a gravelly, cobbly stream bottom. In the lower reaches where the gradient is less and flow is often slower, deposition of the "fines" eroded above begin to drop out. The separates of sand, silt, and some clay begin to cover the coarser elements. Except where trapped in still water areas, these fines tend to be in constant motion to ever lower elevations.

Two elements of bottom stability are rated in this item: (1) Changes or shifts from the natural variation of component size classes and (2) the percentage of all components which are judged to be stable materials. Bedrock, large boulders, and cobble stones ranging in size from one to three feet or more in diameter are considered "stable" elements in the average situation. Obviously, smaller rocks in smaller channels might also be classed as stable. The sizes are given only to guide thought. Bedrock as a major component of bottom and banks, no matter what size the channel or how the other elements rate, always results in an excellent classification of that reach.

1. Excellent: There is no noticeable change in size distribution. The rock mixture appears to be normal for the kind of geologic sources in the basin and the flow forces of streams of this size and location in the watershed.

   If a shift or change has taken place so there are greater percentages of large rock in the small streams and smaller sizes in large streams, the condition class most appropriate should be checked. It is a matter of degree as follows:

   (Stable Materials 80-100%).

2. Good: Slight shift in either direction.

   (Stable Materials 50-80%).

3. Fair: Moderate shift in size classes.

   (Stable Materials 20-50%).

4. Poor: Marked, a pronounced shift.

   (Stable Materials less than 20%).

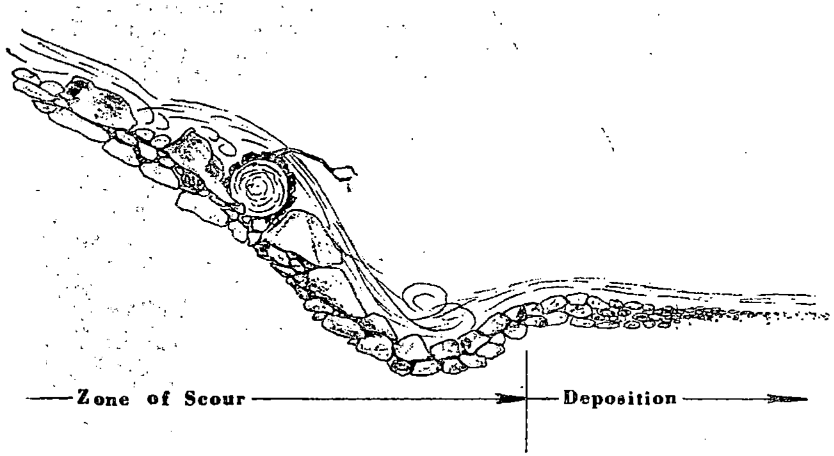
E. Scouring and/or Deposition: Items of size, angularity and brightness already rated above should lead you to some conclusions as to the amount of scouring and/or deposition that is taking place along the channel bottom.

1. Excellent: Neither scouring or deposition is much in evidence. Up to 5% of either or a combination of both may be present along the length of the reach; i.e., 0-5 feet in 100 feet of channel length.

2. Good: Affected length ranges from 5 to 30%. Cuts are found mostly at channel constrictions or where the gradient steepens. Deposition is in pools and backwater areas. Sediment in pools tends to move on through so pools change only slightly in depth but greatly in composition of their size classes.

3. Fair: Moderate changes are occurring. 30 to 50% of the bottom is in a state of flux. Cutting is taking place below obstructions, at constrictions and on steep grades. Deposits in pools now tend to fill the pool and decrease their size.

4. Poor: Both cutting and deposition are common; 50% plus of the bottom is moving not only during high flow periods but at most seasons of the year.



F. Aquatic Vegetation: When some measure of stabilization of the soil-rock components is achieved, the channel bottom becomes fit habitat for plant and animal life. This process begins in the slack water areas and eventually may include the swift water portions of the stream cross section. With a change in volume of flow and/or sedimentation rates, there may also be a temporary loss of the living elements in the aquatic environment. This last item attempts to assess the one macro-aquatic biomass indicator found to best express a change in channel stability.

Clinging Moss and Algae: These lower plant forms do not have roots but cling to the substrate. They are low growing and may first appear as a green to yellow-green slick spot on the bottom rocks. Moss plants continue with slight variation in color but no great change in mass form season to season. Algae by contrast have a peak of growth activity and then die off in great numbers. The slippery conditions they produce persist after death, however.

Both algae and moss inhabit the swift water areas as well as the quiet pools and backwater portions of the stream bottom.

1. Excellent: Clinging plants are abundant throughout the reach from bank to bank. A continuous mat of vegetation is not required but moss and/or algae are readily seen in all directions across the stream.

2. Good: Plants are quite common in the slower portions of the reach but thin out or are absent in the swift flowing portions of the stream.

3. Fair: Plants are found but their occurrence is spotty. They are almost totally absent from rocks in the swifter portions of the reach and may also be absent in some of the slow and still water areas.

4. Poor: Clinging plants are rarely found anywhere in the reach. (This is an unusual situation but could happen under a combination of adverse environmental conditions).

Channels with this much moss are rated "Excellent"

Management Implications

After beating the brush, getting your feet wet and fighting insects, you have established a series of channel ratings. You may now ask, "What do these numbers mean and how are they used in making a management decision?".

By now you know this subject is complicated and precludes indepth answers here. The following brief answers may satsify you of they may raise more questions. When this happens, it's time to consult your Forest hydrologist for detailed, specific answers.

The numbers and the adjective ratings they relate to mean what they say. A stream channel reach that rates "poor" has a combination of attributes that will require more judicious upstream management of the tributary watershed lands than one rated "excellent". This rating procedure was not designed to fix blame for poor land and water management or to reward good management, although, in time, it could be used for this purpose. Before passing judgment, be aware that natural, undistrubed watersheds may exhibit poor hydologic conditions. Conversely, a highly developed and used watershed may have a drainage network in good hydologic shape. The rating system will therefore have the most value to land managers who have definite water management goals, who can relate these to impacts of other resource uses and activities, who understand natural limitations, and are willing and able to use the system to define the risks they are willing to take to maintain or alter the status quo.

One use of this rating system is to assess conditions and define impacts along short reaches of stream. Channel conditions can be evaluated in terms of stream stability and potential for damaging water quality at culvert and bridge sites, at campgrounds and administrative sites or wherever livestock and wildlife concentrate near or across a water course. A channel rated "poor" at a culvert site, for example, cannot withstand as much constriction or gradient change as one rated "good". Armed with this additional knowledge, the decision could be to change locations, redesign the intallation or select a different type of structure to protect the aquatic habitat.

The primary use of this system is to assess entire channel systems within a watershed and to use the results in conjunction with other hydrologic analyses to augment silvicultural prescriptions. Rapid changes in the density and areal extent of vegetation on a watershed can increase stream discharges. Channel systems rated "excellent"

can withstand these increases with less damage than systems rated "poor". "Poor" systems can withstand gradual changes better than abrupt changes in the discharge regimen.

To calculate an overall rating for a stream system, (1) multiply the length of each reach by its numeric rating, (2) add the weighted products of all reaches in the system and (3) divide by the total length of the system.

For example:

Reach A	:	3.2 miles x 80 (fair)	= 256
Reach B	:	0.5 miles x 100 (poor)	= 50
Reach C	:	2.0 miles x 40 (good)	= 80
Total	:	5.7 miles	386

Stream system average: 386 ÷ 5.7 = 68 (Good)

Land and water should not be managed on the basis of averages. In the above example, the stream system is composed of three reaches which rate "good" on the average, but a "weak link" has been identified. Reach B is in "poor" condition. One of the obvious uses of this system is to identify "weak links" and to discover what, if any, opportunity exists to correct the condition. It matters little if the damaged area is natural or man-caused. The discovery of "weak links" should reasonably alter upstream land management to the extent necessary to achieve stated land and water management objectives.

The procedures should ultimately serve as a check and a measure of management success. The net effects of each new increment of change within the watershed management unit will ultimately be expressed in the condition of the stream channel responding to a new hydraulic regimen. Prudent managers will seek these trend data by periodic reappraisal of channel conditions and respond to adverse changes before impacts to the water resource become unacceptable and unalterable.

This large stream channel reach would be rated "excellent" overall.

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